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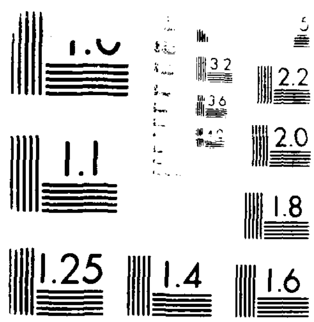

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An Investigation of the Ability to Recover from Transients Following Failures for Single-Pilot Rotorcraft

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SUMMARY

A moving-base simulation was conducted to investigate a pilot's ability to recover from transients following single-axis hard-over failures of the flight control system. The investigation was performed in conjunction with a host simulation that examined the influence of control modes on a single pilot's ability to perform various mission elements under high-workload conditions. The NASA Ames large-amplitude-motion Vertical Motion Simulator (VMS) was utilized, and the experimental variables were the failure axis, the severity of the failure, and the airspeed at which the failure occurred. Other factors, such as pilot workload and terrain and obstacle proximity at the time of failure, were kept as constant as possible within the framework of the host simulation task scenarios. No explicit failure warnings were presented to the pilot. Data from the experiment are shown, and pilot ratings are compared with the proposed handling-qualities requirements for military rotorcraft. Results indicate that the current proposed failure transient requirements may need revision.

INTRODUCTION

The ability of the pilot to recover from the transient motion which follows many types of failures is of paramount importance to aircraft manufacturers and operators, both civil and military. For manufacturers, provision for adequate recovery capability may be a determining factor when designing control power and control authority into a new helicopter, and for operators, it may dictate new training procedures and monitoring equipment. The proposed update to MIL-H-8501, the Handling Qualities Requirements for Military Rotorcraft (ref. 1), outlines requirements for the capability to recover from varying levels of transients following failures (table 1). These requirements were hypothesized, however, and insufficient flight-test and simulation data existed to verify their applicability. Therefore, the simulation discussed in this report was designed to validate or update the proposed requirements.

The investigation was carried out as part of a host simulation that was designed to investigate the ability of a single pilot to conduct demanding tactical mission tasks with different control modes under high workload conditions (ref 2). The high level of pilot workload designed into the host experiment was important, since it provided sufficiently for pilot preoccupation with the flight task to prevent anticipation of the failures.

Using table 1 as a guide, failure levels were defined as uncommanded attitude excursions in specified intervals of time or as step changes in acceleration. Single-axis hard-over failures in the automatic flight control system (AFCS) of the advanced digital optical control system (ADOCS) (ref. 3) were used to achieve the excursions. As a result, the pilots were left with the primary flight control system (PFCS), which utilizes only forward-loop shaping of the controls, for recovery in the failed axis. A step input replaced the output of the AFCS, and the size of this step determined the severity of the failure. To allow the pilot to

assess quantitatively the effects of the simulated failures, a failure rating scale was designed to complement the Cooper-Harper Pilot Rating scale (ref. 4). This report describes the experiment, presents the results, and makes suggestions for further investigations.

BACKGROUND

Previous attempts at defining specifications for transients following failures provided qualitative common sense approaches to the problem without specifying quantitative criteria. Chalk et al. (ref. 5) specify the following for transients following failures of the flight control system (FCS): "Failure-induced transient motions and trim changes resulting either immediately after failure or upon subsequent transfer to alternate control modes shall be small and gradual enough that dangerous flying qualities never result." Regarding single failures of any component or system, reference 5 states, "The aircraft motions following sudden aircraft system or component failures which might occur during maneuvering flight or unattended trimmed flight shall be such that dangerous conditions can be avoided by pilot corrective action. A realistic time delay between the failure and initiation of pilot corrective action shall be incorporated when determining compliance." The proposed revision to this document (ref. 6) retains these criteria.

The first of the statements from references 5 and 6 just given is taken from MIL-F-8785B (ref. 7). A small but important change was made to MIL-F-8785B in its update to MIL-F-8785C (ref. 8). This change deliberately deletes the phrase "small and gradual enough" since it was noted that it may be to the pilot's benefit to experience a noticeable transient after the failure in order to alert him or her to a failure. In fact the experience of General Dynamics with the B-58 (ref. 9) led them to suggest that a minimum allowable transient be specified. Their reasoning was that the previously low allowable transients of reference 7, that would result from soft failures could lead to a catastrophe if the pilot did not detect the failure. For MIL-F-8785C it was decided to change only the previously noted wording without quantitatively specifying a minimum allowable transient following failure. The proposed MIL-F-83300 revision of reference 6 did not reflect this change.

The quantitative requirements for transients following failures of MIL-F-8785C are: "With controls free, the airplane motions due to failures shall not exceed the following limits for at least 2 sec following the failure, as a function of the Level of flying qualities after the failure transient has subsided: 1) For Levels 1 and 2, a $\pm .5$g incremental normal or lateral acceleration at the pilot's station and $\pm 10°$ per sec roll rate, except that neither stall angle of attack nor structural limits shall be exceeded. In addition, for Category A (flight that requires rapid maneuvering, precision tracking, or precise flight-path control), vertical or lateral excursions of 5 ft and ± 2 deg. bank angle. 2) For Level 3, no dangerous attitude or structural limit is reached, and no dangerous alteration of the flight-path results from which recovery is impossible."

The proposed criteria in reference 1 stem from previous specifications for the in-flight and ground handling qualities of the UH-60A (ref. 10) and the AH-64A helicopters (ref. 11). Both of these specifications place angular rate and translational acceleration limits on the helicopter transient response to a failure. Reference 10 states that "with the automatic stabilization and stability augmentation equipment engaged, and from steady level flight for a period greater than 30 sec, out-of-trim conditions resulting from abrupt disengagement or from abrupt single failure of the equipment to a hard-over position in a single axis shall be such that with controls free for 3 sec following the disengagement or failure, the resulting rates of yaw, roll, and pitch shall not exceed 10° per sec and the change in normal acceleration shall not exceed ± 0.5g." Note that these requirements differ from the fixed-wing requirements only in the length of the time interval. For failures of a single power-operated control system, reference 10 retains the same limits, but states that the limits apply to trimmed level flight speeds above 80 knots. Reference 11 employs the same criteria for failures of the automatic stabilization equipment. As reference 1 explains, the criteria in reference 1 do not explicitly address 1) loss of control, 2) structural limit exceedence, or 3) collision with nearby objects. The proposed specification covers items 1 and 2 by stating that in forward flight the aircraft must stay within the Operational Flight Envelope and item 3 by the position excursions that result from the specified acceleration limits. Transient failure limits are also defined for both hover and low speed, while both references 10 and 11 cover only the forward flight portions of the aircraft flight envelope.

EXPERIMENTAL DESIGN

In this section, the current failure-recovery requirements are reviewed. Also, experimental variables along with the failure-insertion technique that uses the ADOCS control logic are described, and the failure recovery rating scale is introduced.

Current Specification

The proposed update to MIL-H-8501, Handling Qualities Specification for Military Rotorcraft (ref. 1), states that "the transient following a failure or combination of failures shall be recoverable to a safe steady flight condition without exceptional piloting skill." It also states that the perturbations encountered will not exceed the limits of table 1. As the table shows, the specification is broken into two speed regimes where hover and low speed are defined as speeds less than 45 knots. Near-earth operations are defined as operations sufficiently close to the ground or objects fixed on the ground such that flying is primarily accomplished with reference to outside objects. The levels 1, 2, and 3 boundaries are defined as Cooper-Harper ratings of 1-3.5, 3.5-6.5, and 6.5-9.5, respectively (ref. 4).

Figure 1, taken from the Background Information and Users Guide for reference 1, shows time histories of the attitudes, attitude rates, and body axes accelerations in addition to the explicit limits in 3 sec, as given in table 1. As shown, the attitude failures are assumed to produce a constant attitude rate, whereas the axial failures are assumed to produce linearly increasing body-axis accelerations. As mentioned earlier, the limits proposed in table 1 are hypothetical; the purpose of this experiment was to validate, or provide data to revise, these limits.

Experimental Variables

Experimental variables for this investigation were the failure axis, the magnitude of the failure, and the aircraft airspeed at the time of the failure. Other factors such as pilot workload, altitude, and terrain and obstacle proximity also play an important role in the pilot's ability to recover from certain failures. The proposed requirements do not specify these conditions at the time of failure and, therefore, essentially similar conditions were maintained for all the simulated failures. This was possible since the pilots had to follow the strict mission scenario of the host simulation (to be discussed) which kept flight path, altitude, and terrain proximity similar for the mission task elements of all runs.

Flight Control System and Failure Insertion

A model-following control system, described in detail in reference 3, was used to examine the failure modes. The output of the model to be followed is fed into a structure that approximates a unity transmission via a simple premultiplied plant inversion in combination with a high-gain feedback stabilization loop for robustness and disturbance rejection.

The FCS is divided into two parts (fig. 2): (1) a primary flight control system (PFCS), and (2) an automatic flight control system (AFCS). The PFCS provides the pilot with a reversion mode that consists of simple forward-loop shaping of his command signals to the control actuators. The AFCS contains the desired feed-forward command model along with the feedback laws that provide disturbance rejection as well as minimization of the effects of plant parameter variations. The output of the AFCS passes through some port limiting (fig. 3) and is then summed with the output of the PFCS. The port limiting provides partial safeguard against hard-overs of the AFCS. Signals from the AFCS are divided between a high-frequency-compensation path and a low-frequency-trim followup path. The high-frequency path has a low-authority limit; thus any hard-over from the AFCS is attenuated by the combination of this low-authority limit and the rate limit in the low-frequency trim path.

Block diagrams of PFCS in all four axes are shown in figure 4. Each axis, except for the directional axis, has a nonlinear shaping function, a sensitivity gain, and a derivative

rate limiter. All axes, except for the vertical axis, have a lead-lag shaping function. The outputs of these four control axes enter a control mixing network that attempts to decouple the aircraft response to control input.

The aircraft responses to step inputs are shown in figures 5-8. These responses were generated using the stability derivative model of the UH-60 in hover (ref. 3) This model is shown again in figures 9 and 10. Concatenated in front of this model were the lead-lag shaping functions or gain (fig. 4). The input magnitude for each of the responses is the equivalent stick displacement in inches.

For this investigation, failures were simulated by disconnecting the output of the AFCS (prior to the port limiting) and replacing it with a step whose magnitude would determine the severity of the failure. As a result, the states that were fed back to the FCS computer no longer influenced the system response after the failure. The pilot was therefore required to recover the aircraft with only the PFCS in the failed axis which provided only forward-loop shaping of his commands.

Failure Rating Scale

The Cooper-Harper pilot rating scale is generally used to evaluate the handling qualities of aircraft, both in flight testing and in ground simulation. In this investigation, however, both handling qualities and the pilot's ability to recover from a failure were of interest. It was felt that if the Cooper-Harper scale alone was used, the pilot would not be answering the questions that are directly relevant to failure recoveries. Also, certain keywords take on slightly different definitions in the context of a failure state. For example, workloads are typically very high while attempting to recover from a failure and as a result, "tolerable workloads" need to be redefined. Finally, even though the Cooper-Harper scale deals with the question of flight safety, it is not explicitly broken down in the Cooper-Harper decision tree for the case of an ongoing failure.

A new rating scale was therefore designed specifically for rating the ability to recover from the abrupt transient motion following a failure (fig. 11). The scale format is similar to a turbulence-effect rating scale discussed in reference 12. The design of this scale is similar to the Cooper-Harper scale in that certain key questions separate blocks of ratings. The first question in the decision tree serves simply to separate a crash from a recovery. The next question deals with safety of flight issues and separates those failures which endanger the aircraft and crew (level 3) from those that require appreciable effort for recovery but are not safety-critical (level 2). The final question in the tree quantifies the effort required to recover as noticeable (level 2) or negligible (level 1). Note that the failure rating scale uses letters instead of numbers to avoid confusion with the Cooper-Harper scale. This Failure Rating Scale was subsequently used to define and evaluate the monitoring concept for the NASA V/STOL Research Aircraft in reference 13.

As mentioned above, the failure rating scale was designed to complement the Cooper-Harper scale. Therefore, certain correlations between the two scales must be clearly defined. The failure rating scale consisted of three levels, defined similarly to the Cooper-Harper levels. For example, a failure rating level-1 (FRL 1) failure was considered to be a mild failure requiring only minimal increase in pilot workload. In the Cooper-Harper terminology, at most only mildly unpleasant deficiencies result from a FRL 1 failure and only minimal additional pilot compensation is required for desired performance. Note the relative nature of the failure rating scale as opposed to the absolute nature of the Cooper-Harper scale. Minimal pilot compensation in the failure rating scale refers to the pilot compensation required in addition to the pilot compensation required prior to the failure. Therefore, an aircraft having level-2 handling qualities (requiring considerable pilot compensation for adequate performance), may have a FRL 1 failure causing it to require minimal additional pilot compensation. Also note that the failure scale applies only to the interval of the transient motion following the failure.

Since a combination of the severity of the failure and the handling qualities of the post-failure aircraft determine the ease of recovery, the rating scales are coupled. Therefore, to interpret each rating, the other rating must be known. Depending on the size of the failure, however, either the failure rating or the Cooper-Harper rating takes precedence. For a mild failure, the handling qualities of the post-failure aircraft determine the ease of recovery and therefore the Cooper-Harper rating is more informative. In the case of a severe failure, however, the failure rating takes precedence because a level-1 aircraft may crash just as easily as a level 2.

INVESTIGATION FACILITIES

The investigation was conducted as part of a simulation study of the effects of advanced flight control and display systems on the ability of a single pilot to perform various tactical military missions (ref. 2). A summary of the facilities used for the host simulation follows.

Vertical Motion Simulator

The six-degree-of-freedom, large-amplitude-motion Vertical Motion Simulator (VMS) was used for the evaluations. Figure 12 shows the VMS and its motion amplitude and rate limits. The large-motion capabilities of the VMS make it an ideal tool for failure simulations. It provides ample motion cueing to the pilots, allowing them to detect failures even while looking inside the cockpit. This ability adds a necessary degree of realism to the experiment, as indicated by the following postrun comment:

> As soon as I was sitting there very stable at a hover, suddenly I felt the vertical motion moving down. I looked up and saw the altitude dropping rapidly, grabbed

the collective and pulled, and I pulled very hard to get it to stop. (Pilot 3, Vertical level 1-2, Rating: F)

The motion logic is set up such that translational accelerations and rotational rates from the aircraft's model are input into filters whose effect is to wash out all translational and rotational displacements (up to constant acceleration inputs) (fig. 13). The motion gains and washout frequencies for this experiment are given in table 2. The gains and washout frequencies are the low speed constants below 30 knots, the high speed constants above 60 knots, and a linear interpolation between the low and high speed constants for speeds between 30 and 60 knots. Note that all of the motion gains are less than unity. Thus the pilot feels only a percentage of the acceleration in the model. This may have a deleterious effect on cueing as discussed later.

Advanced Cockpit

The cockpit instrumentation was patterned after the displays currently used by the Army Advanced Rotorcraft Technology Integration program. The flight controls were side-stick controllers for both cyclic and collective (Measurement Systems Incorporated limited-displacement force controllers) and limited-displacement pedals that were used for directional control. The setup was similar to the ADOCS 2-1-1 configuration – a right-hand controller for pitch and roll and a left-hand controller for the vertical axis (ref. 3). The force displacement gradients for the side sticks were all identical and equal to 1.82 lb deg. The pedals had a force gradient of 40 lb in with a breakout of 6 lbs. These gradients were selected from reference 3. Instead of the usual helicopter instrumentation, the pilot was provided with an instrument package consisting of two CRT displays (fig. 14). One of the displays was used as the mission-management display (MMD) to provide aircraft and weapons status information (ref. 2). The other display served as the tactical-situation display (TSD), a moving map display, to show the pilot his location and the locations of both enemy and friendly elements (ref. 2). Note that even though the MMD could have been used as a failure warning device, it was not used due to reasons discussed later.

Head-Up Display

In addition to the MMD and the TSD, a head-up display was used to portray flight-path management information, such as altitude, airspeed, and heading, to the pilot. The head-up display operated in one of four selectable modes, namely hover, bob-up, transition, or cruise. Figures 15 and 16 show the Hover and the Cruise head-up displays, respectively. This HUD is based on the AH-64 Apache Helmet Mounted Display/Pilot Night Vision System display format. Almost all the failures were injected while the head-up display was in one of these two modes.

Evaluation Pilots

A NASA research pilot flew several preliminary flights and then assisted in the development of the failure rating scale. Subsequently, five active-duty U.S. Army helicopter pilots participated in the experiment, two of whom flew the entire test matrix of the host simulation. Although each Army pilot was a highly experienced helicopter pilot, all had only limited experience and training in research system evaluations and some had little experience with ground simulators. However, each pilot was given ample time to fly the simulator and familiarize himself with the system prior to evaluation flights.

PROCEDURE

The following sections describe the experimental task, the pilot briefing, and the data collection methods used.

Task

Since the failure transient experiment was conducted as part of a host simulation, the failures were inserted while the pilots were performing some portion of the task simulation for that scenario. The host simulation mission consisted of five distinct tasks: 1) ingress, 2) air-to-ground engagement, 3) battle-damage assessment, 4) air-to-air engagement, and 5) egress. Failures were injected during the ingress, battle-damage assessment, and the egress phases only. However, the pilots were told that a failure could occur at anytime.

The ingress phase involved nap-of-the-earth (NOE) flight at around 60 knots from a departure waypoint A to a waypoint B within the battle area. In addition to flying and navigating the aircraft, the pilot had the mission management tasks of providing the battle captain with status reports and enemy encounters or sightings. If fire was received, the pilot was to report the encounter and mark the position by pressing a button on the perimeter of the TSD. Upon reaching waypoint B, the air-to-ground engagement was initiated by directing the pilot towards an enemy tank positioned nearby. After the tank was destroyed, the battle-damage-assessment (BDA) phase was initiated. The pilot was instructed to move to a hover position close to the destroyed tank (which would be there regardless of who won the air-to-ground engagement) and conduct and transmit a BDA. The BDA information consisted of the responses to preprogrammed prompts which appeared on the MMD. While the aircraft was in hover, the BDA information had to be entered on the keyboard. All the vertical failures were inserted during this phase. Next, the pilot would be instructed to intercept and engage an enemy helicopter trying to penetrate the forward line of troops in his vicinity. No failures were inserted during this phase. The final portion of the mission

was egress and a return to base. This phase was frequently used to insert either low-speed NOE or high-speed up-and-away failures by altering the scenario to force the pilots to reach the required flight conditions.

As mentioned previously, failures in each axis were created by replacing the corresponding AFCS signal with a predetermined, constant, step input. The magnitudes of the steps were chosen to create the desired attitude excursion in 3 sec (table 1) for each failure level, assuming that no recovery action was taken by the pilot. The pilots, however, were allowed to begin recovery as soon as a failure was detected.

The basic task was to recover the aircraft to a safe flight condition. A safe flight condition was nominally defined as one that would allow a safe return to base. The ultimate definition of a safe flight condition, however, was left to the pilots, since it would depend on the situation. After the pilot had recovered and flown the degraded system long enough to be able to evaluate it, the simulation was stopped and the pilot was asked to give a failure rating for his ability to recover and also a Cooper-Harper rating for his ability to complete the combat mission with the degraded control system.

Reference 1 states that "all crew members will be provided with immediate and easily interpretable indications that a failure has occurred and what corrective action is appropriate." However, to avoid the question of how to best notify the pilot of a failure and the appropriate corrective action no means of failure indication were used for this experiment. Therefore, aside from the uncommanded motion of the aircraft, the pilots had no indication that a failure had actually occurred.

Pilot Briefing

In addition to the briefing to familiarize the pilots with the advanced cockpit and the complicated mission scenario of the host simulation, the pilots were given a briefing on the design, objective, and approach of the failure transient experiment. In particular, the pilots were introduced to the new failure rating scale and were briefed on how to make maximum use of it in conjunction with the Cooper-Harper scale.

Data Collection

All the relevant variables, including aircraft states, failure injection points, and pilot inputs were recorded on strip charts and magnetic tapes, the latter to allow subsequent computer-aided analyses. These analyses included the determination of pilot-response-time delay obtained by measuring the time between failure injection and first recovery action, using plots of control motion vs. time. Also, the entire postrun pilot commentary was recorded for each run, including the Cooper-Harper and the failure ratings.

RESULTS

In reviewing the following results, it should be kept in mind that the post-failure handling qualities were dependent on the magnitude of the failure. Since the failure of the AFCS causes some of the available control power to be used to trim out the failure, for large failures the resulting maneuvering control authority in one direction can be marginal. Pilot comments and ratings for all runs indicate that, for most of the runs, the pilots considered the post-failure aircraft (PFCS in the failed axis only) to possess inadequate handling qualities for the task (completing the combat mission), based on Cooper-Harper ratings collected along with failure ratings (fig. 17). However, the controllability of the post-failure system was rarely in question.

Longitudinal Axis

The longitudinal failures were injected at three airspeeds: hover, 60 knots, and 100 knots. Of the five longitudinal failures injected at a hover, two were at the proposed maximum level-2 values and three at the level-3 values as presented in Table 1. Of the nine longitudinal failures injected at 60 knots, one was at level 2 and eight were at level 3. Finally, the failure injected at 100 knots was a level-3 failure. Figure 18 is a graphical compilation of the failure rating data in the longitudinal axis.

For the uncommanded attitude excursions in a hover, the major problem seemed to be the tendency for a pilot induced-oscillation (PIO) initially following the failure, as the following comments indicate:

> Ok, was recovery impossible? Almost, but "No" it wasn't. Was safety of flight compromised during recovery? "No", marginally. Was a significant amount of effort required to recover? Definitely "Yes". It was noticeable. I will give it an "E", poor. Too many PIOs. Even me relaxing on it and everything else. (Pilot 2, Longitudinal level 2, Rating: E)

This tendency can be attributed partially to the degraded handling qualities of the simulated ADOCS PFCS as compared to the AFCS. In any case, level-3 failures (24° attitude change in 3 sec) seemed too large to be countered effectively in a precise hover-hold situation, e.g., hovering in a masked position, and were mostly rated FRL 3. The specified values from reference 1 seem quite acceptable for hover, as may be seen from figure 18. Note that almost all the hover ratings fall within the boundaries of the same magnitude and rating levels.

The results were not as clear for the forward flight (60 and 100 knots) cases. Again, the major difficulty seemed to be PIOs following the attempt to correct the initial attitude excursion. Pilots commented that in an NOE environment, this tendency to cause a PIO in pitch can very well be fatal.

> I would say it was very poor and give it a rating of "Foxtrot." Specifically, for the purpose of the fact that we're flying low level and NOE in the close proximity of trees and obstacles in route, and I can't stand those pitch oscillations of 15 to 20 to 30 degrees uncommanded, especially, when I've got my attention diverted to other things like handling the MMD, trying to plug in coordinates, and trying to talk on the radio all at the same time. (Pilot 2, Longitudinal level 3, Rating: F)

The results were also inconsistent from pilot to pilot, as shown in figure 18. One of the pilots consistently rated all failures in all axes to be unrecoverable. Another pilot, on the other hand, rated the same level-3 failure from "B" (very good, negligible amount of effort required to recover, FRL 1) to "E" (poor, noticeable amount of effort required to recover, FRL 2).

A look at pilot-response time delay (defined as the interval between failure insertion and the first major control input in the corresponding axis) for some of the longitudinal failure cases (fig. 19) did not help explain this spread. However, it was noticed that the response times for the milder failures were somewhat longer. Interestingly, it was also noted that failures at a hover seemed to take longer to detect.

In summary, the data suggest that the specifications may be satisfactory for the hover case, whereas the specifications for the forward flight case cannot be conclusively validated or rejected.

Lateral Axis

Preliminary evaluations suggested that the proposed level-1 lateral failures were exceedingly mild and therefore, only values based on the maximum level 2, level 3, and more severe failures in both hover and forward flight (60 knots) were evaluated. Figure 20 is a graphical presentation of the data.

For the lateral-axis failures in a hover, the major problem seemed again to be the PIOs as a result of initial overcontrol.

> It took me four or five overshoots, probably pilot induced oscillations, to get it down to some kind of controllable level. I almost flew into the mountain on my right. If I had been in a tight hover hold when that happened, it would have been all over, because I would have immediately went right into the trees, and I wouldn't have been able to react fast enough to save the aircraft. (Pilot 3, Lateral level 3, Rating: G)

The extent of overcontrol seemed to be directly related to the mission-management task being performed at the moment of failure insertion. Pilots commented that the motion

system sufficiently enabled them to detect uncommanded motion of the aircraft even while looking inside the cockpit.

> I was looking down and I'm going "whoa, something is going wrong" and I looked up and there I was at a 30° bank. (Pilot 2, Lateral level 3, Rating: H)

However, some complained that the lack of detail in the computer-generated imagery often caused them to judge their initial attitude incorrectly.

As seen from figure 20, the hover data points fall either within or just outside the boundaries of the same magnitude and rated levels. The "H" rating given by pilot 2 for the level-3 failure in a hover may be explained based on his pilot-response-time delay. Because he was preoccupied with reporting his location during the simulated mission, he failed to detect the failure for almost 5 sec then, apparently surprised by the attitude excursion, he drove the aircraft too hard, causing an unacceptable PIO. His comments indicate that the PIO caused him to rate the failure unrecoverable.

> I reached over on the map, and I was looking down at it when I started noticing the failure. I let go of the map. I tried to recover, and it was just one PIO to the other laterally, and there's no way for me to recover. (Pilot 2, Lateral level 3, Rating: H)

For the forward-flight case, the data suggest that the current specifications are restrictive. As figure 20 shows, almost all data points fall to the right of the boundaries of the same magnitude and rating levels. Note that failures more severe than the specified level 3 of 24° in 3 sec were used to determine when FRL 2 and FRL 3 failures are actually reached. A possible revision of the specifications for the forward-flight lateral failures is suggested by figure 21. The new boundaries are constructed by defining the specified level 3 to be the new level 1 and the next two (more severe) levels to be the new levels 2 (32° in 3 sec) and 3 (70° in 3 sec) respectively. As may be seen, a majority of the forward-flight points fall within the appropriate new boundaries.

A partial plot of failure rating vs. pilot-response-time delay may be used to explain some of the inconsistencies. For example, pilot 5 rated the same new level-2 failure both a "B" (very good, negligible amount of effort required to recover, FRL 1) and an "E" (poor, noticeable amount of effort required to recover, FRL 2). Figure 22 shows that for the failure rated a "B", pilot 5 responded in approximately 0.25 sec whereas for the one rated an "E", the response time was approximately 0.75 sec. From figures 23 and 24, it can be seen that the additional time resulted in an attitude excursion which was three times as large at the end of the 0.75-sec delay compared to the 0.25-sec delay. The difference of 6° may not seem significant by itself, but the ensuing PIO resulted in a maximum attitude change of 39° for

the longer detection period compared to 19° for the shorter one. This difference is quite significant and probably caused the difference in ratings.

A difference in average response time between failures in pitch and roll was observed. A comparison of figures 19 and 22 reveals that the roll failures were, on the average, detected sooner than pitch failures of comparable severity. A possible reason for this may be the means by which the pilots detect errors in pitch and roll in the simulator (and possibly the real world). A horizon line that is not level, whether detected from the computer-generated image or from an instrument with an artificial horizon, is a quick indicator of an attitude error in roll for level flight. Errors in pitch must be detected from biases of the entire horizon: thus they may be harder to detect.

In summary, the current specifications seem to be adequate for failures in a hover. However, revision of the forward flight specifications may be warranted.

Directional Axis

The results for failures in the directional axis were inconclusive, as shown by figure 25. Pilot 1 again considered the only failure he was given (level 3) to be unrecoverable, whereas the data for the other pilots were scattered. Pilot 2 generally rated similar failures easier to recover from than pilot 3. Both, however, rated identical failures very differently at different times.

Nevertheless, the data indicate that the directional-axis failure specifications are too restrictive. Since all the data points fall to the right of the boundaries of the same magnitude and rating levels in figure 25. Note that, because recovery from the specified level-3 failures is considered easy a new, more severe, failure level was also examined. The spread of the data makes it impossible to suggest a new set of specifications, as given for the lateral axis.

A plot of failure rating vs. pilot-response-time delay was made as an attempt to explain some of the scatter. As may be seen from figure 26, a few of the inconsistencies may be explained. For example, pilot 3 rated the new level-2 failure once a "C" (good, noticeable amount of effort required to recover, FRL 2) and another time an "F" (very poor, safety of flight compromised during the recovery, FRL 3). Considering the severity of the failure, the slight difference (increase) in response delay may explain the worse rating. Even using pilot-response-time delay to explain some of the spread, the data remain too scattered to point to any definite conclusions.

Vertical Axis

The severity of vertical axis failures was measured based on the resulting vertical acceleration. As may be seen from table 1, the specifications define incremental accelerations of

0.05, 0.2, and 0.4 gs within 3 sec as level-1, level-2, and level-3 failures, respectively. All three levels were examined in a hover only, as shown in figure 27.

A majority of the vertical failures of all levels, except specification level 1, were rated as impossible recoveries (fig. 27), caused mainly by the inability of the pilots to detect sinking motion of the aircraft. This inability seemed to refer mainly to cases where the pilots were looking inside the cockpit while performing a mission management task. However, even when looking outside the cockpit, the computer-generated imagery seemed to afford sufficient cueing of the downward motion only when very close to the ground. Additionally, pilot comments indicated (1) a failure detection and warning system was needed to aid them in initiating recovery as soon as possible and (2) the need to release the collective side-stick controller to free a hand for mission management tasks had an appreciable effect on recovery.

> In a normal situation in flight, single-pilot cockpit, I'm going to have to use one of my hands. I can't use the cyclic because of the sensitivity of it, so I am having to release my collective. That's causing me to not monitor 100% on that collective. It is, on a single-pilot-cockpit type environment, it is impossible to expect the pilot to have to maintain hands on the control 100% of the time. (Pilot 2, Vertical level 3, Rating: H)

Almost all of the failures which occurred while the pilot was performing a mission-management task involving the use of his left hand were rated unrecoverable.

Additional levels were defined between levels 1 and 2 to further explore the acceleration at which the change from recoverable to unrecoverable occurs. As figure 27 shows, almost all failures at or above the new level 1.6 (with a maximum acceleration of 0.11gs) were considered unrecoverable. Since only a few runs were done with smaller accelerations, the accelerations corresponding to FRL 2 and FRL 3 cannot be determined. The data, however, suggest that the current failure specifications are too lenient for a NOE environment. The specified accelerations for each level need to be reduced. The magnitude of the reduction, however, cannot be determined because of insufficient data.

DISCUSSION OF RESULTS

A general observation for all the runs was that the existence of direct failure-warning instrumentation in the cockpit would have had an appreciable effect on the recovery. This is especially true for the less severe level 1 and 2 failures, which were at times detected very late or not at all.

> (You had a collective failure) I did? (Yes) If I did, I didn't notice it. (Pilot 2, Vertical level 2, Rating: A)

Another possible reason for the inability to detect the less severe failures may be due to the motion feedback to the pilot. Although the visual scene integrates the model acceleration correctly and gives the pilot the full effect of the failure, the motion system first attenuates the magnitude of the failure by the motion gain and then washes it out to zero. The latter effect should go unnoticed by the pilot, but the former effect directly reduces the acceleration cue to the pilot by 30%. These effects lead to conservative results since, in the actual aircraft, the pilot will have better motion feedback cues. Since the visual cues in the real world also will be better, they lead to conservative simulation results.

Some of the pilots expressed a need for a device that would inform them of exactly what had failed and which systems were affected.

> I would rather have some more aircraft systems telling me that that's what I have. In other words, if I have a longitudinal axis failure on my flight control system, I would like to have a light that says it or something comes on saying, "hey, you have a failure" ...I was in question whether it was me flying bad or the aircraft having a failure. I really wasn't sure. (Pilot 2, Longitudinal level 2, Rating: C)

Such a device can be especially useful for the milder failures. In fact, an argument may be made that in the absence of failure-warning instrumentation, mild failures may be dangerous since they may go undetected until a recovery is impossible, especially in high-workload situations.

> I had my attention outside, trying to make a radio call, thinking about a battle damage assessment, looking for the enemy, and thinking about programming in the report. With all of these other things on my mind, I don't have time to be monitoring the flying that close, and I don't think I would have caught it in time, so I'm going to give it an "H". (Pilot 3, Vertical level 2, Rating: H)

Therefore, a high fidelity monitoring system can be crucial in dealing with the milder failures.

Some general comments follow. 1) For hover and low speed, the attitude excursion specifications do not distinguish between failures based on how and when (within the 3-sec period) the maximum attitude is reached. Such distinctions may be important. For example, a failure which causes a large initial attitude change which levels off as the maximum excursion is reached, may be more severe than one with a slow initial attitude change on the way to the same maximum value. This is true especially in the presence of failure warning systems that would allow the pilot to become aware of the latter type of failures before the attitude change becomes too large. Therefore, additional attitude-rate specifications may be desirable to further clarify severity levels.

2) Similarly, for translational accelerations, the manner in which the maximum acceleration for each level is reached is not clearly specified. From the figures provided in the Background Information and Users Guide to MIL-H-8501, it appears that a linear increase in acceleration has been used to define corresponding rates and displacements. Linearly-increasing axial accelerations may be physically unrealistic. For hover and low-speed flight, a hard-over in the vertical axis will produce a step in acceleration that becomes washed out as the vertical velocity increases. In fact, it is difficult to see what type of failure in the vertical axis would cause a linear increase in acceleration for hover and low-speed flight. It seems more reasonable to change the proposed specification to reflect step time-histories in the vertical axis rather than ramps. Step accelerations are also desirable because they result in the maximum possible rates and displacements.

3) The same situation exists for the forward flight case. It is assumed that the accelerations increase linearly to the maximum allowable in the specified interval of time depending on the level. Again, a step increase in acceleration may be more appropriate. Current specifications do not distinguish between such failures (a step as opposed to a ramp) as long as they do not exceed the maximum specified acceleration. The resulting rates and displacements are sufficiently different, however, to warrant new definitions of the levels.

4) Finally, an important area that the new specification does not cover is a discussion of the regulation of the unfailed axes during recovery. With a hingeless rotor system, the recovery from the failed axis may introduce off-axis rates that must also be regulated. Thus the degree of augmentation left in the unfailed axes may influence the pilot's ability to recover from the failure.

CONCLUSION

A moving-base simulation was performed to determine if the transient failure requirements suggested in the proposed handling qualities requirements for military rotorcraft are satisfactory. The simulation used the ADOCS control law structure with a 2-1-1 side-stick controller mechanization which used two side sticks, one for pitch and roll and the other for collective, and pedals for yaw. Failures were simulated as hard-over failures of the automatic flight-control system in both hover and forward flight. The failures were given to the pilot while under high workload during a simulated mission scenario. No failure warnings were presented to the pilot. Also, the failure mechanization forced the pilot to recover the aircraft with no feedback stabilization in the failed axis. Finally, a failure rating scale was developed to enable the pilot to rate the recovery from the failures accurately.

Results indicate that the proposed criteria for the longitudinal and lateral axes in hover are reasonable while the criteria for the vertical axis appear to be too lenient. The directional axis results were inconclusive in hover. For forward flight, the longitudinal-axis results are inconclusive, while the lateral-axis results suggest that the proposed criteria are too

restrictive, and possible new criteria are defined. Directional-axis forward flight results are also inconclusive.

REFERENCES

1. Hoh, Roger H.; Mitchell, David G.; Aponso, Bimal L.; Key, David L.; and Blanken, Chris L.: Proposed Handling Qualities Requirements for Military Rotorcraft. STI TR-1194-4, Apr., 1987.

2. Mitchell, David G.; Hoh, Roger H.; and Atencio, Adolph, Jr.: Classification of Response-Types for Single-Pilot NOE Helicopter Combat Tasks. Proceedings of the 43rd Annual Forum of the American Helicopter Society, 1987.

3. Landis, Kenneth H.; and Glusman, Steven I.: Development of ADOCS Controllers and Control Laws. Vol. 1, Executive Summary; Vol. 2, Literature Review and Preliminary Analysis; Vol. 3, Simulation Results and Recommendations. USAAVSCOM TR84-A-7; NASA CR-177339, 1985.

4. Cooper, G. C.; and Harper, R. P.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

5. Chalk, C. R.; Key, D. L.; Knoll, J.; Wasserman, R.; and Radford, R. C.: Background Information and User Guide for MIL-F-83300 Military Specification—Flying Qualities of Piloted V/STOL Aircraft, AFFDL-TR-70-88, 1971.

6. Hoh, R. H.; and Mitchell, D. G.: Proposed Revisions to MIL-F-83300 V/STOL Flying Qualities Specification, Naval Air Development Center NADC-82146-60, 1986.

7. Military Specification, Flying Qualities of Piloted Airplanes, MIL-F-8785B, 1969.

8. Moorhouse, D.; and Woodcock, R. J.: Background Information and User Guide for MIL-F-8785C, Military Specification—Flying Qualities of Piloted Airplanes. AFWAL-TR-81-3109,1982.

9. Craig, S. J.; and Ashkenas, I. L.: Background Data and Recommended Revisions for MIL-F-8785B, Military Specification—Flying Qualities of Piloted Airplanes, TR 189-1, Systems Technology, Inc., Hawthorne, CA, 1971.

10. Prime Item Development Specification for Utility Tactical Transport Aircraft System, Specification No. DARCOM-CP-222-S1000C, Aug. 1975.

11. Prime Item Development Specification for Advanced Attack Helicopter, Specification No. DRC-S-H10000B, Apr. 1982.

12. Lebacqz, J. V.: and Aiken, E. W.: A Flight Investigation of Control, Display, and Guidance Requirements for Decelerating Descending VTOL Instrument Transitions Using the X-22A Variable Stability Aircraft. Report AK-5336-F-1, Naval Air Systems Command, Sept. 1975.

13. Schroeder, J. A.; Moralez, E.; and Merrick, V. K.: Simulation Evaluation of the Control System Command Monitoring Concept for the NASA V/STOL Research Aircraft (VSRA), AIAA Paper 87-2255-CP, 1987.

TABLE 1. — Transients due to failures

LEVEL	FLIGHT CONDITION		
	HOVER AND LOW SPEED	FORWARD FLIGHT	
		NEAR EARTH	UP-AND-AWAY
1	3-deg ROLL, PITCH, YAW 0.05g n_x n_y n_z. NO RECOVERY ACTION FOR 3.0 sec	BOTH HOVER-AND-LOW-SPEED AND FORWARD-FLIGHT UP AND AWAY REQTS APPLY	STAY WITHIN THE OFE. NO RECOVERY ACTION FOR 10 sec
2	10-deg ATTITUDE CHANGE OR 0.2g ACCELERATION. NO RECOVERY ACTION FOR 3.0 sec	BOTH HOVER-AND-LOW SPEED AND FORWARD-FLIGHT UP AND AWAY REQTS APPLY	STAY WITHIN OFE. NO RECOVERY ACTION FOR 5.0 sec
3	24-deg ATTITUDE CHANGE OR 0.4g ACCELERATION. NO RECOVERY ACTION FOR 3.0 sec	BOTH HOVER-AND-LOW-SPEED AND FORWARD-FLIGHT UP AND AWAY REQTS	STAY WITHIN OFE. NO RECOVERY ACTION FOR 3.0 sec

OFE: OPERATIONAL FLIGHT ENVELOPE

TABLE 2 — Motion logic gains and frequencies

		Low speed[a]	High speed[b]
GP	Roll gain	0.3	0.2
GQ	Pitch gain	0.3	0.2
GR	Yaw gain	0.3	0.2
GX	Longitudinal gain	0.6	0.3
GY	Lateral gain	0.4	0.3
GZ	Vertical gain	0.7	0.3
ω_p	Roll washout frequency, rad/sec	0.6	0.7
ω_q	Pitch washout frequency, rad/sec	0.5	0.6
ω_r	Yaw washout frequency, rad/sec	0.5	0.6
ω_x	Longitudinal washout frequency, rad/sec	0.7	1.0
ω_y	Lateral washout frequency, rad/sec	0.5	0.7
ω_z	Vertical washout frequency, rad/sec	0.3	1.0

[a]Low speed <30 knots
[b]High speed >60 knots

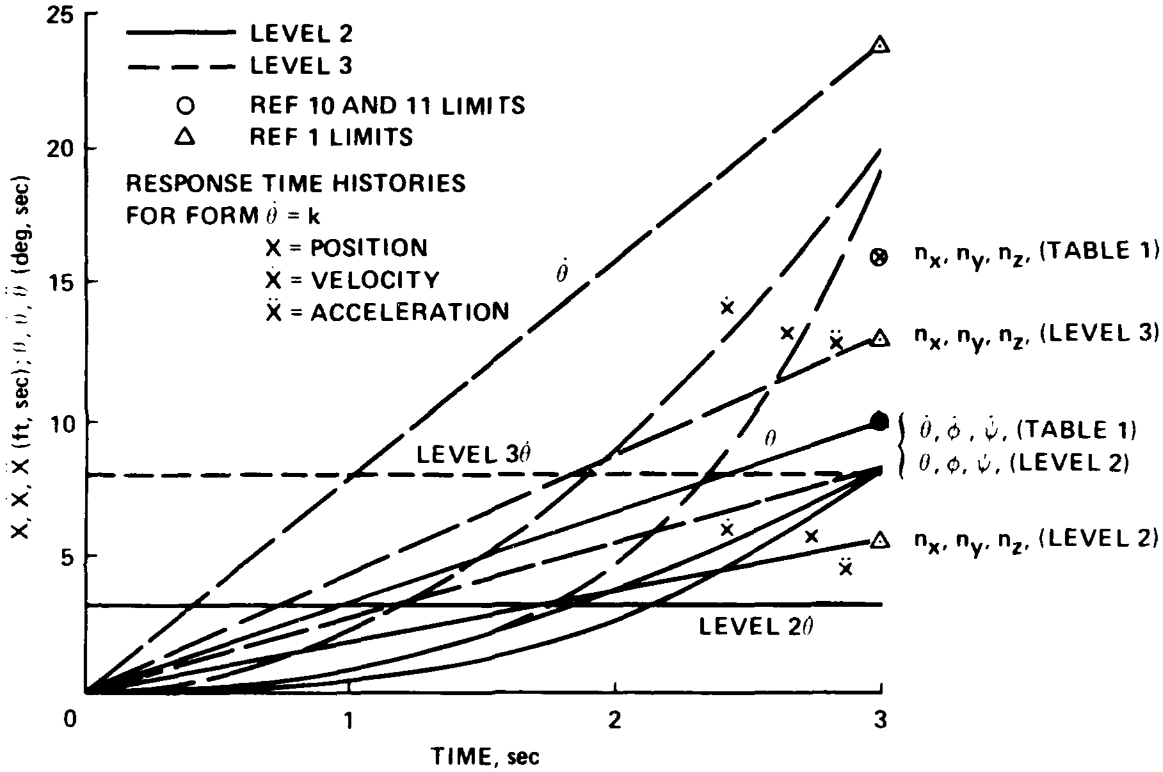


Figure 1. – State time-histories of previous and proposed transient failure criteria (from ref. 1).

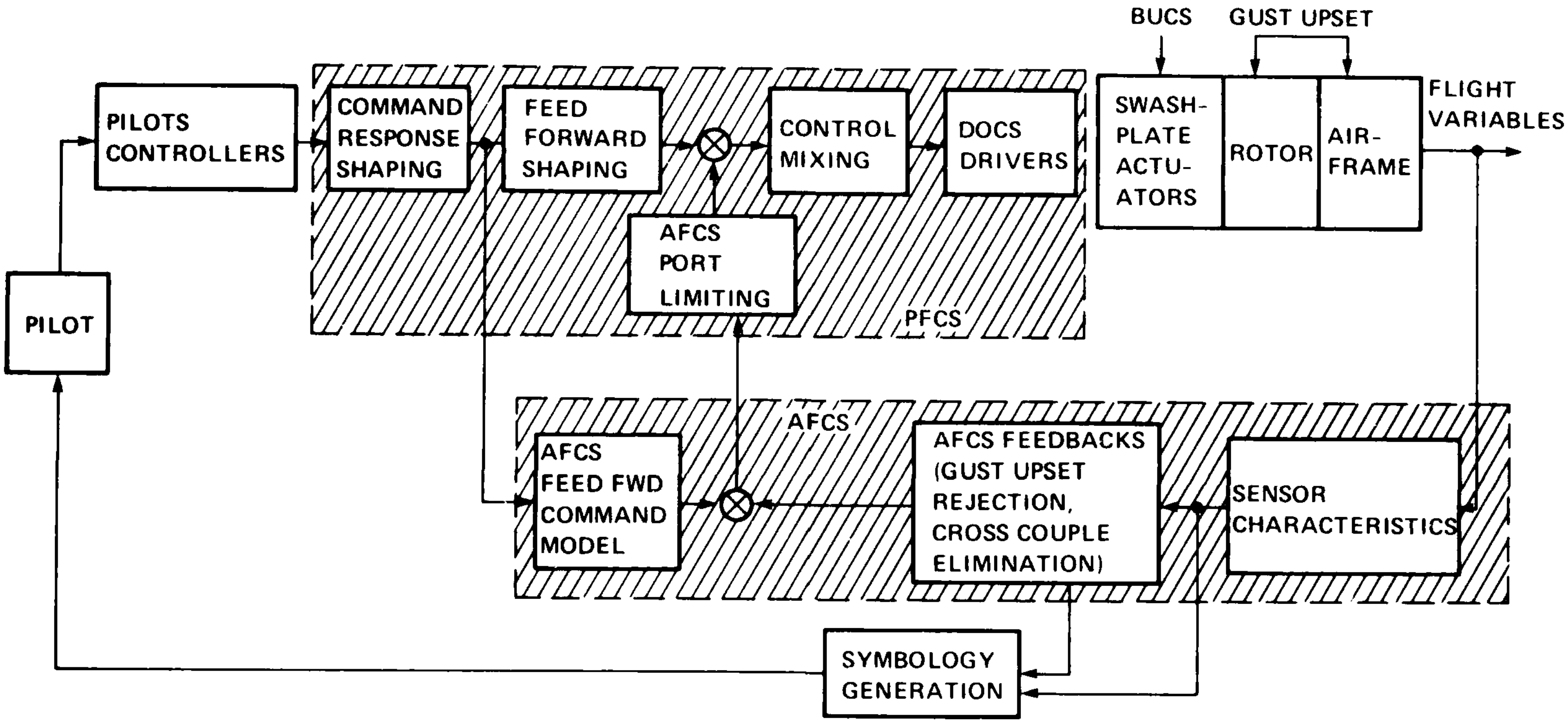


Figure 2. — ADOCS flight-control system concept.

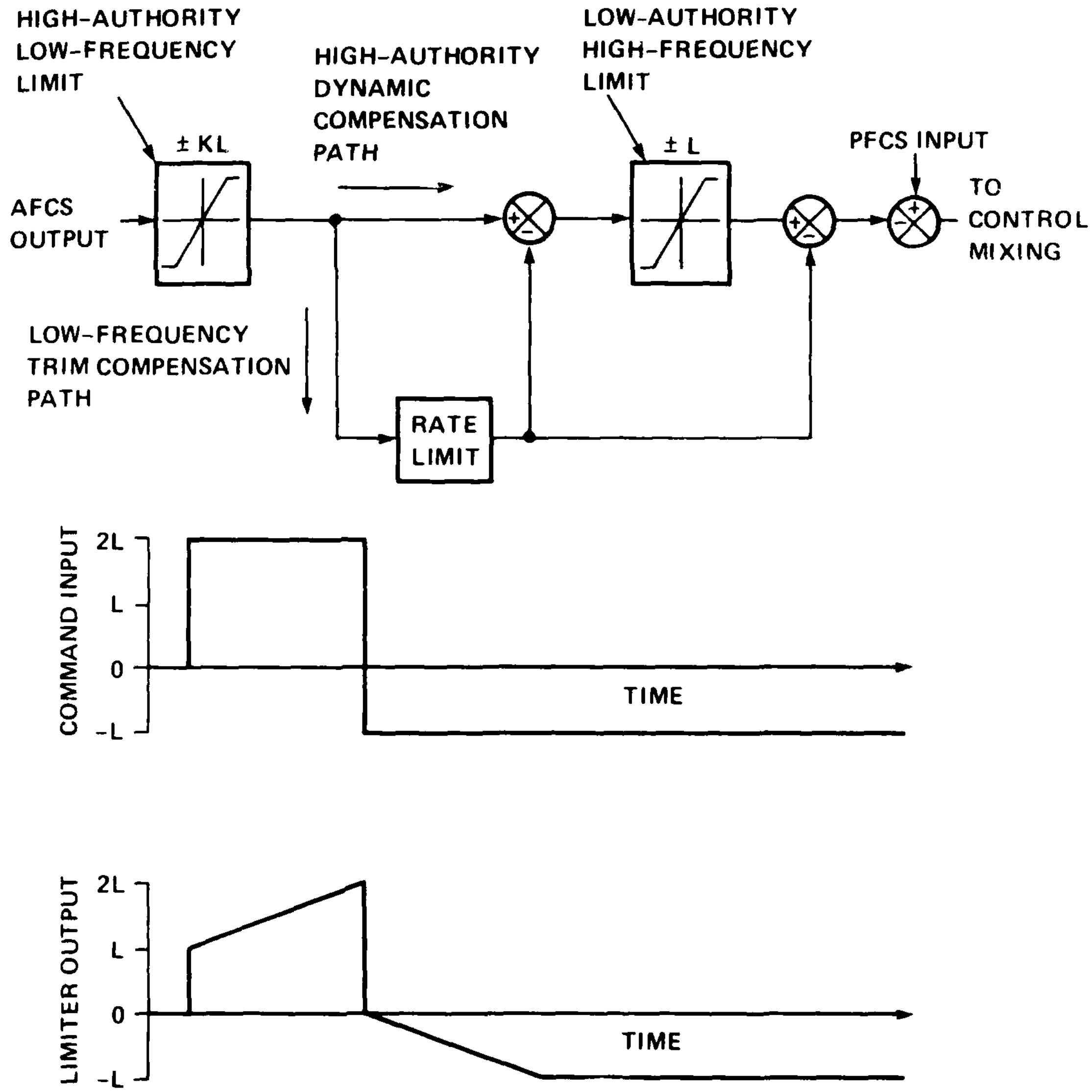


Figure 3. — AFCS-PFCS interface limiter.

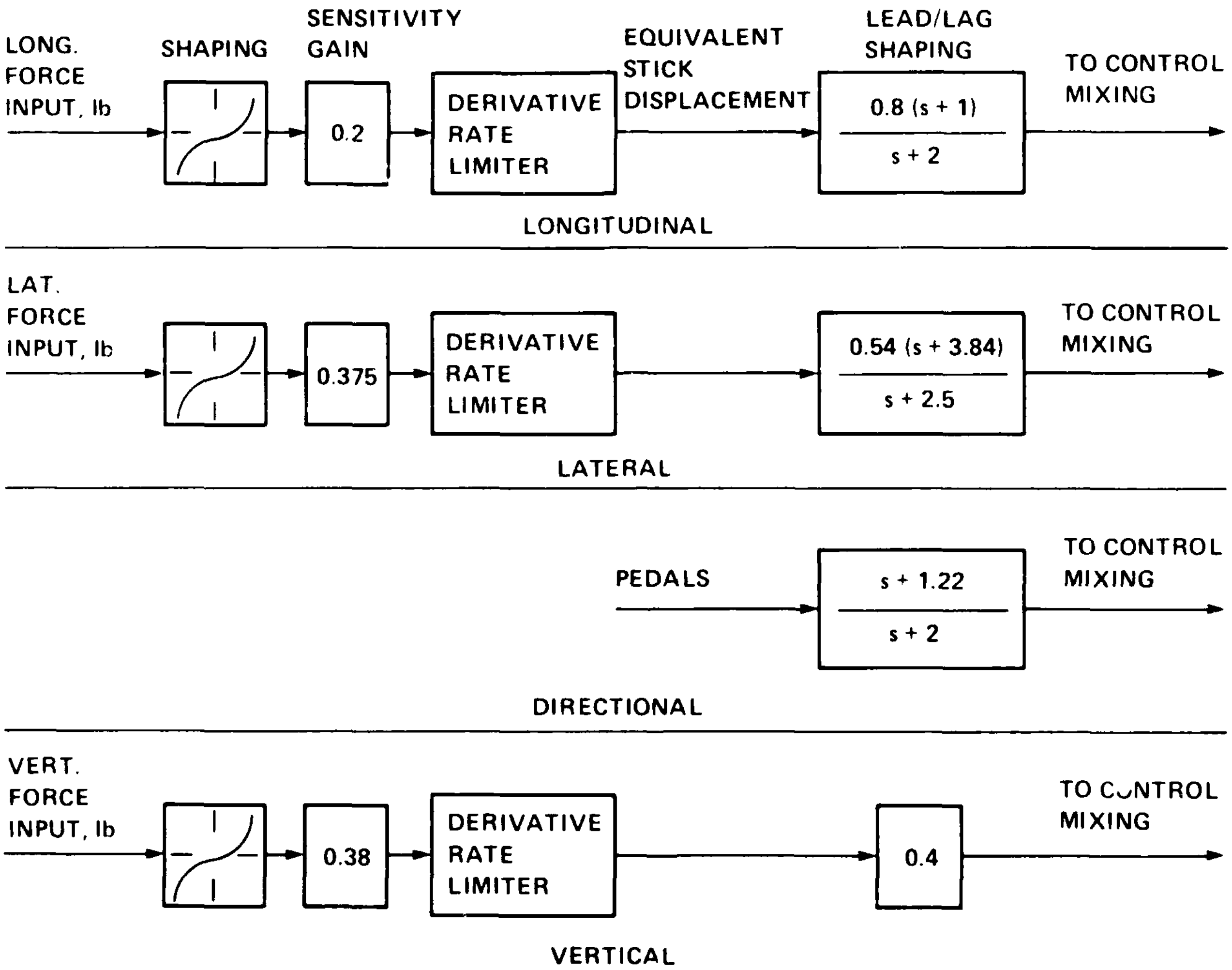


Figure 4. — PFCS block diagram.

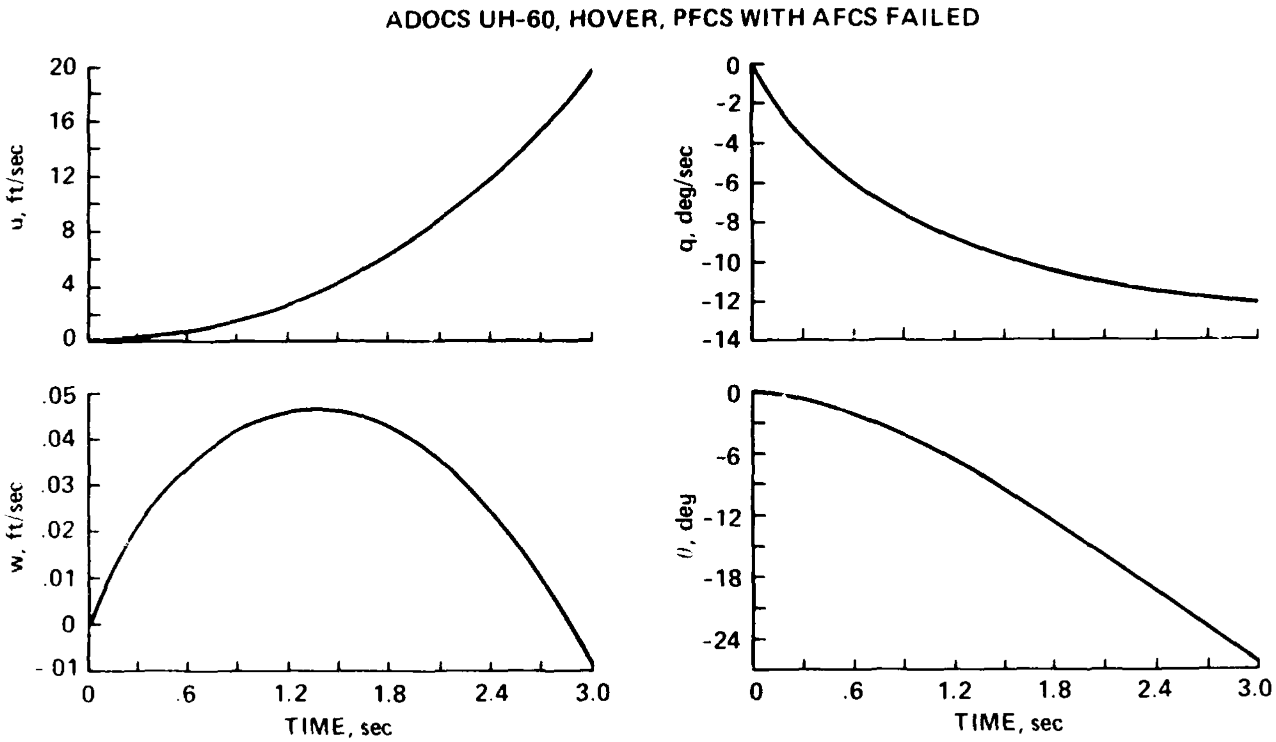


Figure 5. -- Response to an equivalent 1-in. longitudinal cyclic input.

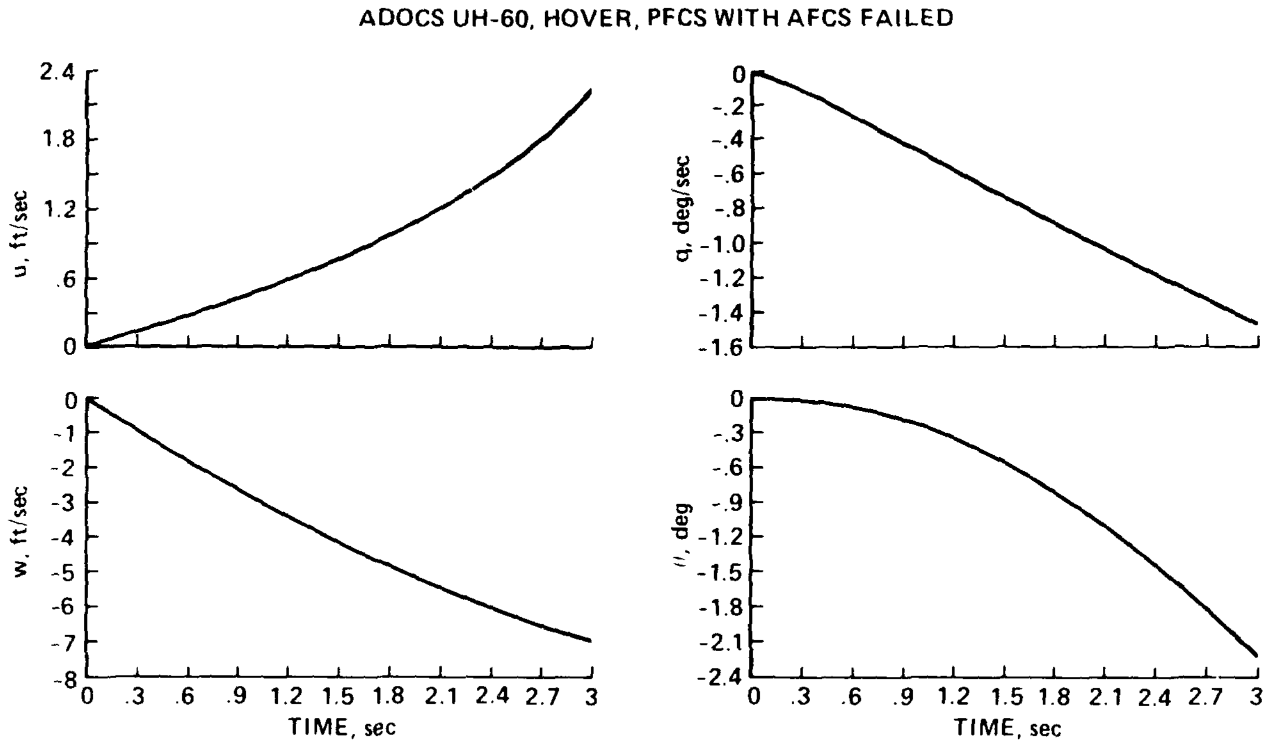


Figure 6. — Response to an equivalent 1-in. collective input.

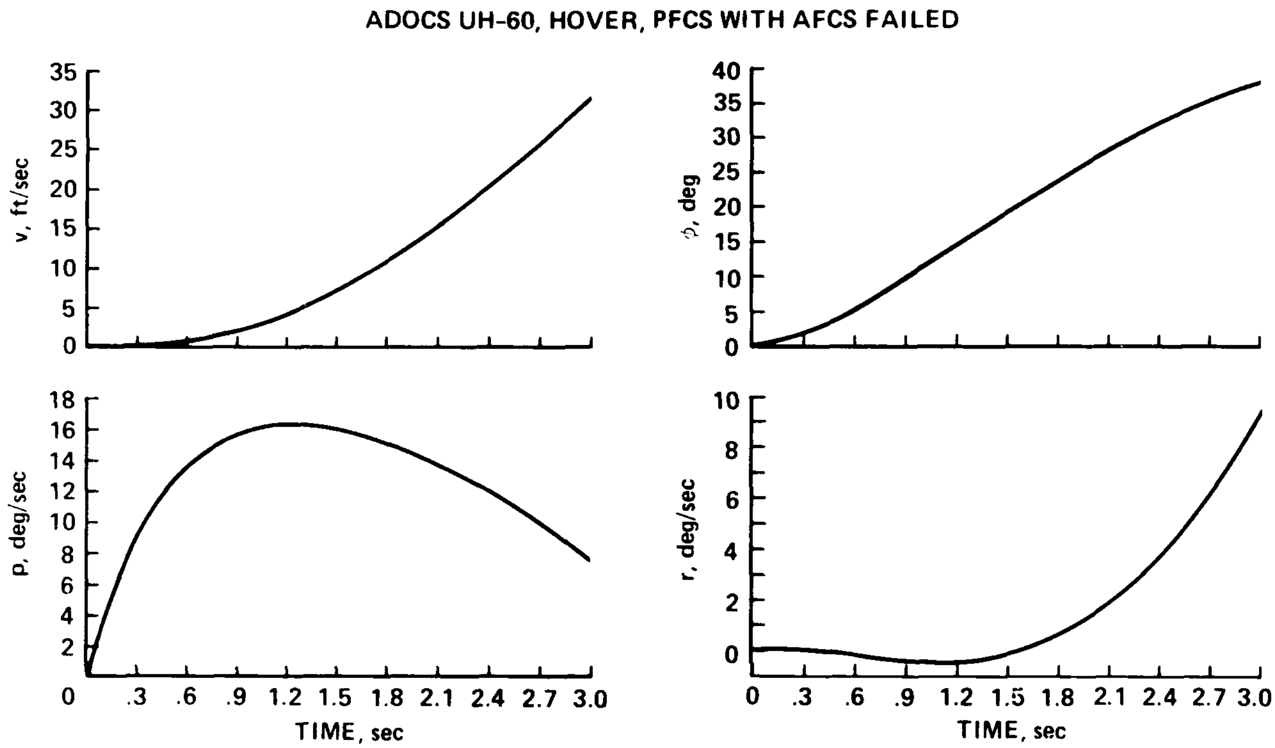


Figure 7. — Response to an equivalent 1-in. lateral cyclic input.

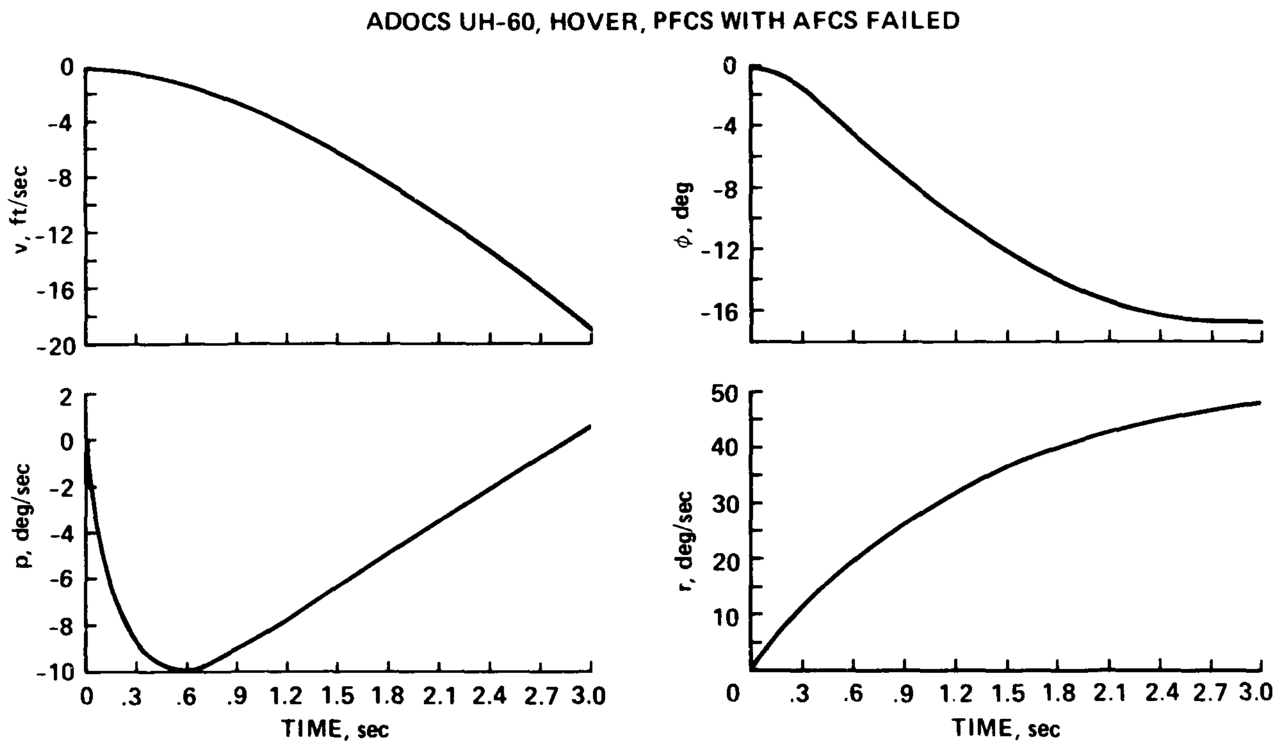


Figure 8. — Response to an equivalent 1-in. pedal input.

$$
\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.015 & 0.0212 & 1.3499 & -32.2 \\ -0.005 & -0.2748 & 0.1135 & 0 \\ 0.0005 & 0.0021 & -0.5193 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 1.7041 \\ 0.1134 \\ -0.3286 \\ 0 \end{bmatrix} \delta_B
$$

$$
\begin{bmatrix} \dot{u} \\ \dot{w} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -0.015 & 0.0212 & 1.3499 & -32.2 \\ -0.005 & -0.2748 & 0.1135 & 0 \\ 0.0005 & 0.0021 & -0.5193 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ w \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} 1.0893 \\ -8.5827 \\ -0.0183 \\ 0 \end{bmatrix} \delta_C
$$

ALL UNITS ARE IN ft. deg, sec

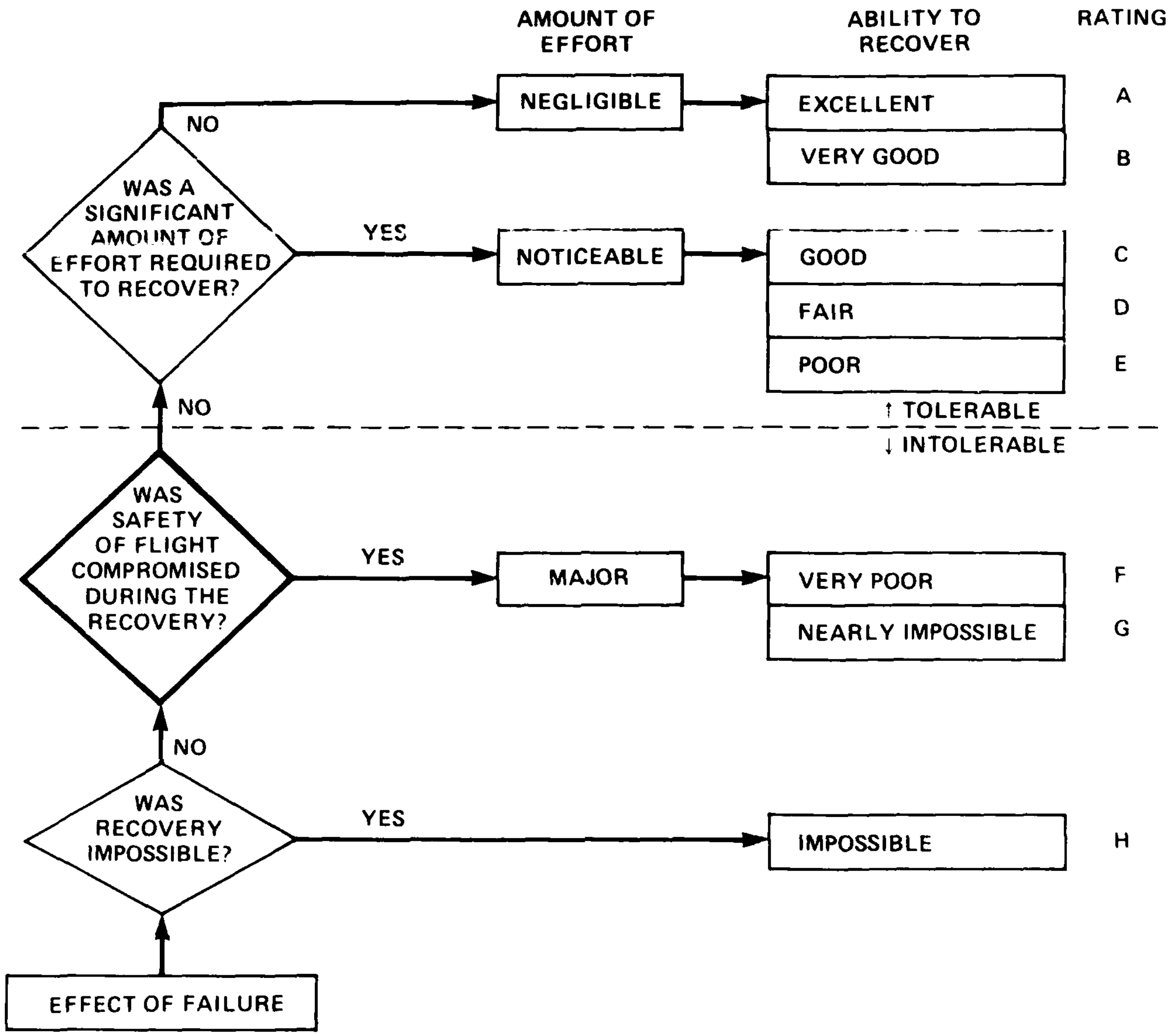
Figure 9. — UH-6C hover longitudinal equations of motion.

$$
\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{\varphi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -0.0465 & -1.5152 & 32.2 & 0.4485 \\ -0.0260 & -3.3484 & 0 & 0.2119 \\ 0 & 1 & 0 & 0 \\ 0.0081 & -0.1856 & 0 & -0.2879 \end{bmatrix} \begin{bmatrix} v \\ p \\ \varphi \\ r \end{bmatrix} + \begin{bmatrix} 0.9664 \\ 1.3118 \\ 0 \\ 0.0266 \end{bmatrix} \delta_S
$$

$$
\begin{bmatrix} \dot{v} \\ \dot{p} \\ \dot{\phi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} -0.0465 & -1.5152 & 32.2 & 0.4485 \\ -0.0260 & -3.3484 & 0 & 0.2119 \\ 0 & 1 & 0 & 0 \\ 0.0081 & -0.1856 & 0 & -0.2879 \end{bmatrix} \begin{bmatrix} v \\ p \\ \phi \\ r \end{bmatrix} + \begin{bmatrix} -1.7151 \\ -0.9313 \\ 0 \\ 0.7153 \end{bmatrix} \delta_R
$$

ALL UNITS ARE IN ft, deg, sec

Figure 10. — UH-60 hover lateral-directional equations of motion.



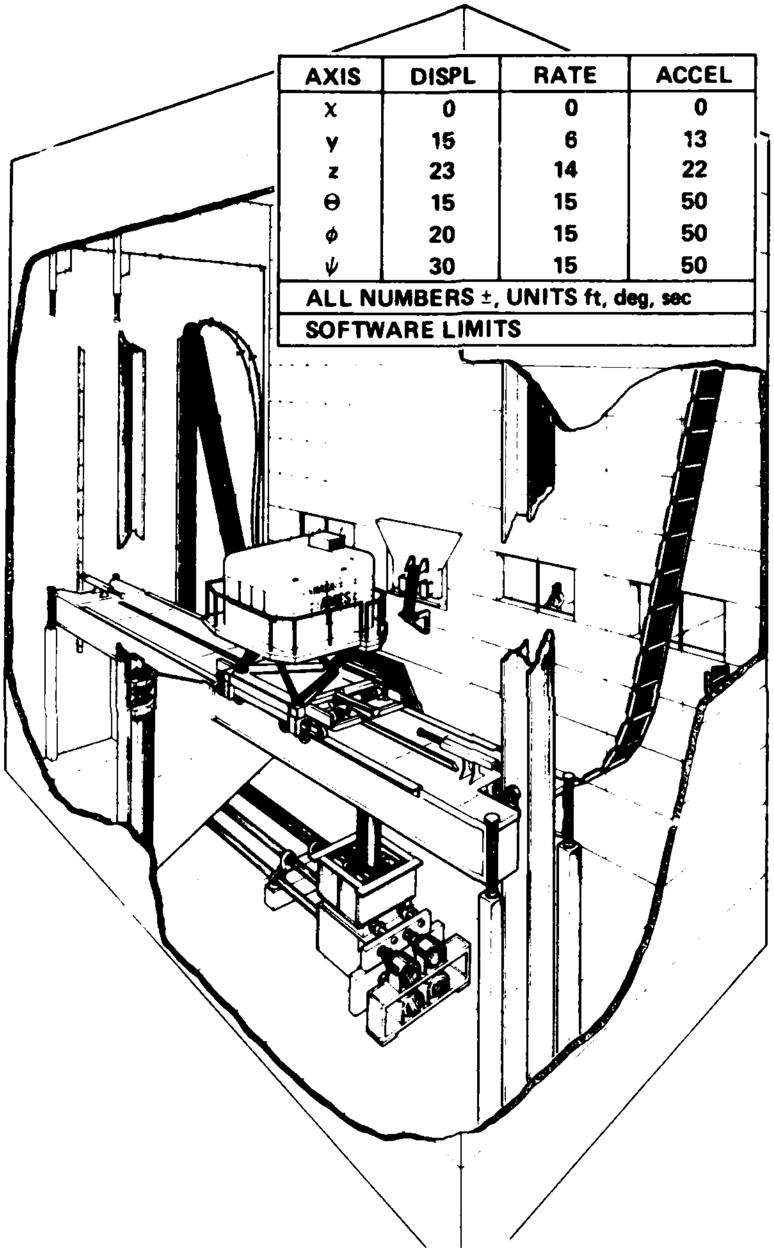
SAFE OPERATING CONDITION = WITHIN BOTH AIRCRAFT AND OPERATIONAL LIMITS

RECOVERY = RETURN TO SAFE OPERATING CONDITION

EFFORT = INTEGRATED PHYSICAL AND MENTAL WORKLOAD REQUIRED TO EXECUTE RECOVERY

COMPROMISE SAFETY OF FLIGHT = CAUSE TO EXCEED EITHER AIRCRAFT OR OPERATIONAL LIMITS OR CAUSE AN ENCOUNTER WITH SURFACE OBSTACLES

Figure 11. — Failure rating scale.



AXIS	DISPL	RATE	ACCEL
x	0	0	0
y	15	6	13
z	23	14	22
Θ	15	15	50
φ	20	15	50
ψ	30	15	50
ALL NUMBERS ±, UNITS ft, deg, sec			
SOFTWARE LIMITS			

Figure 12. — Vertical motion simulator.

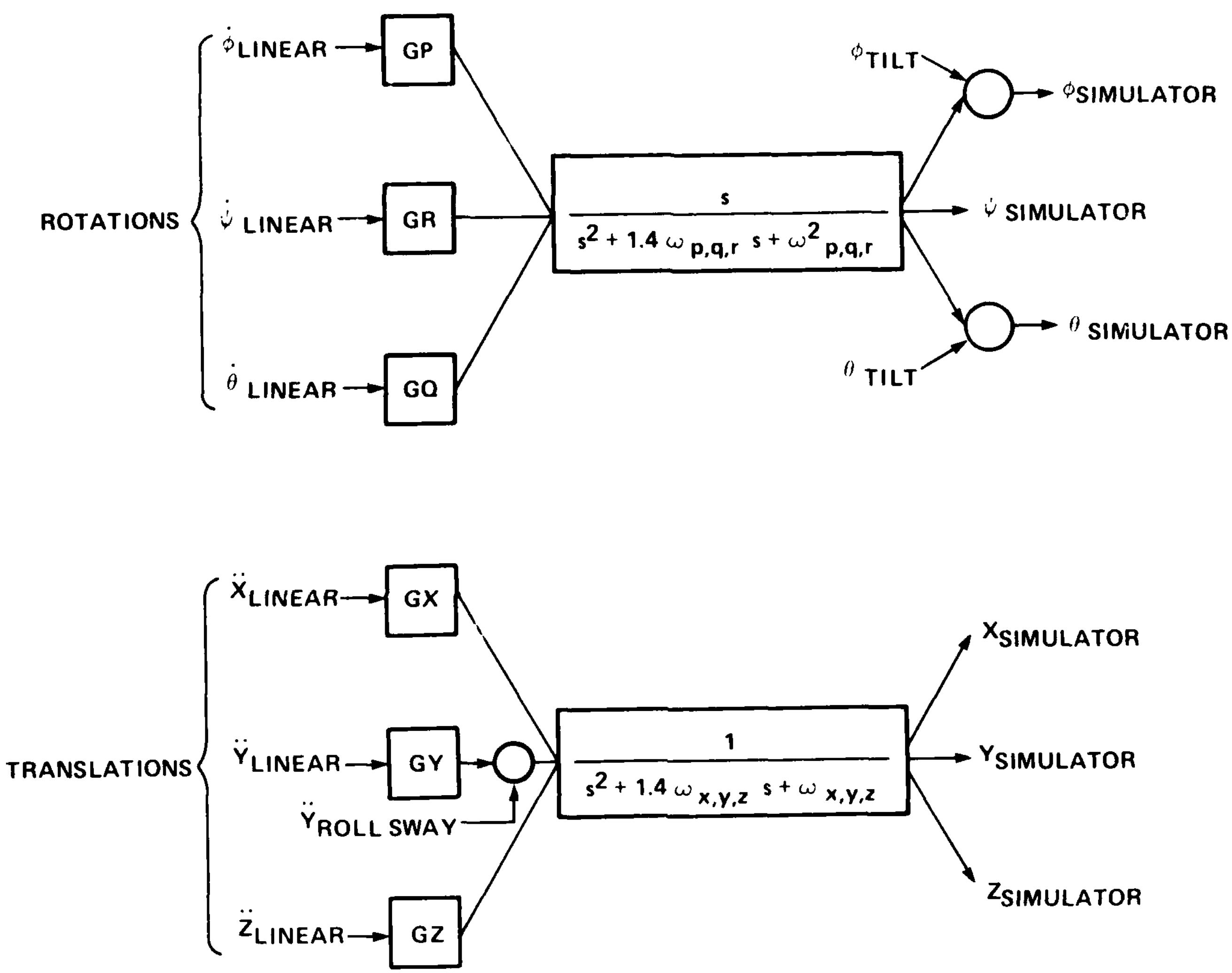


Figure 13. - Motion logic diagram.

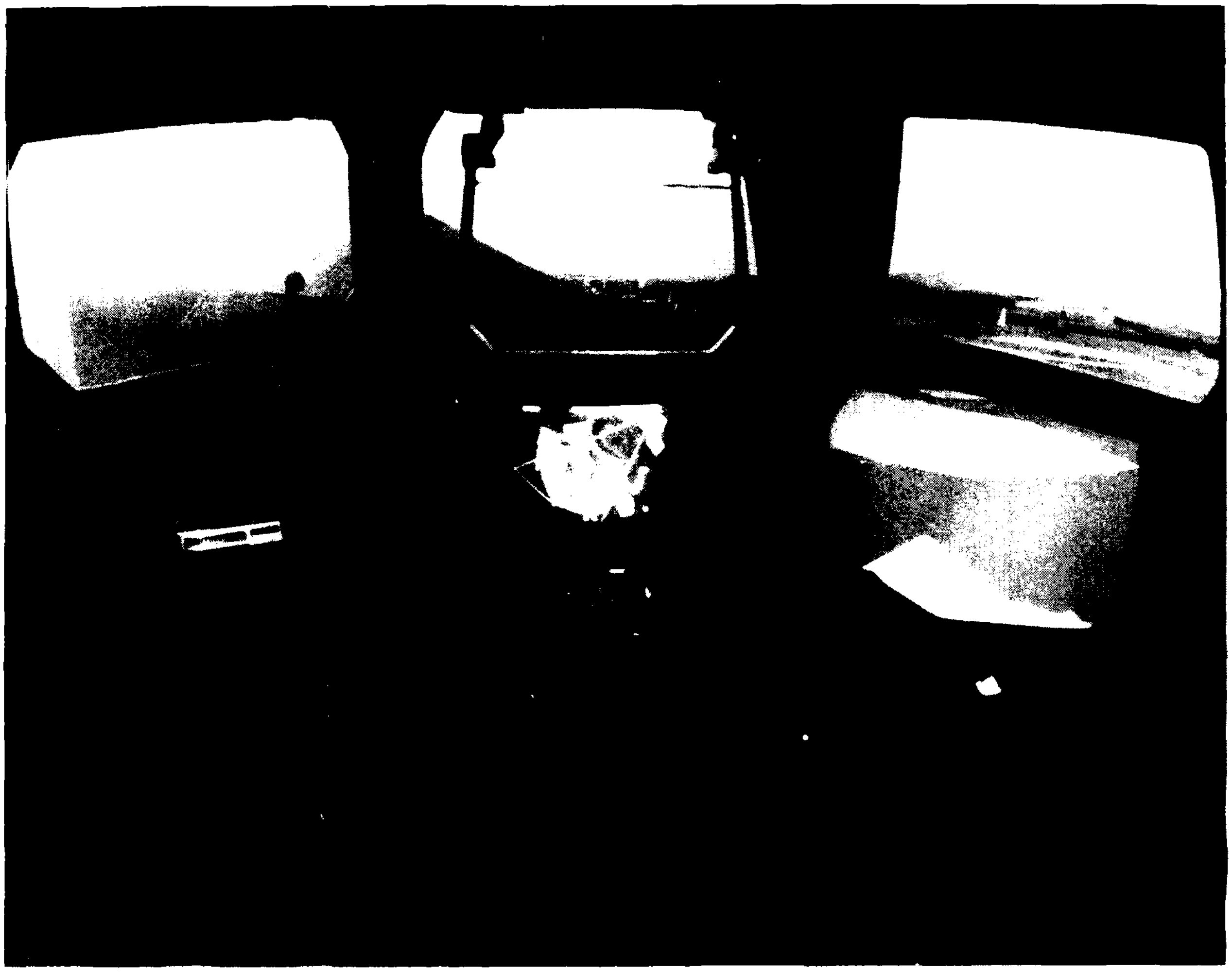


Figure 14. — Simulation cockpit.

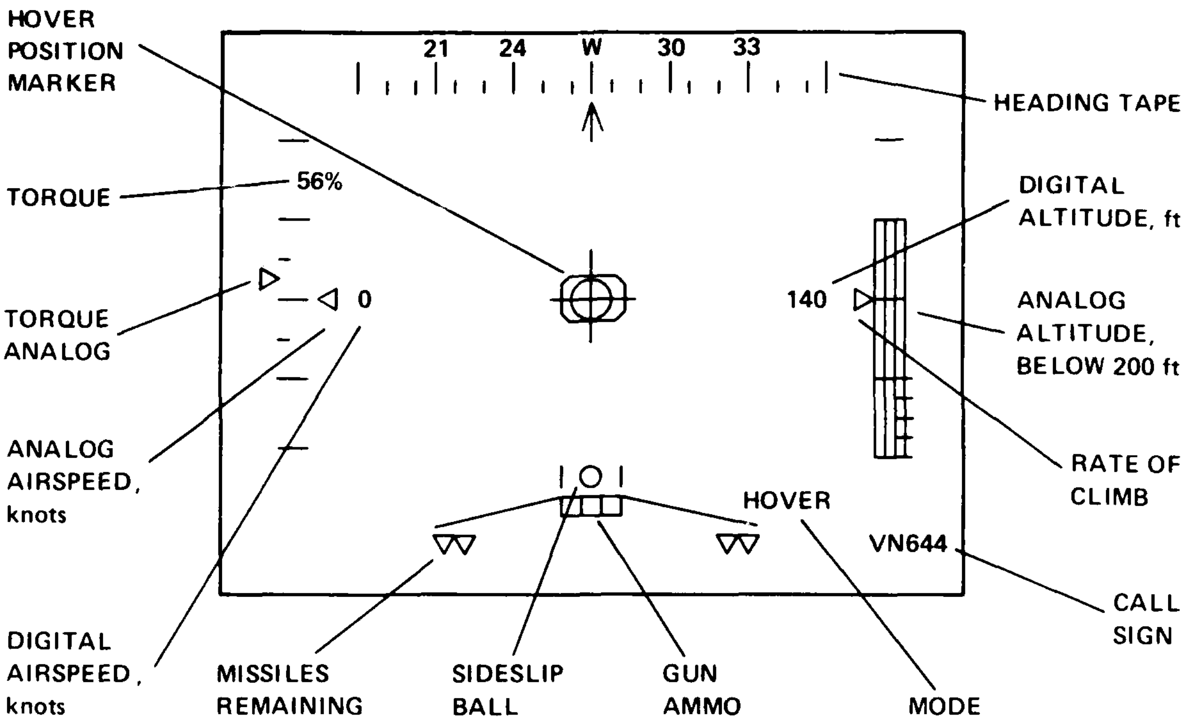


Figure 15. — Hover head-up display.

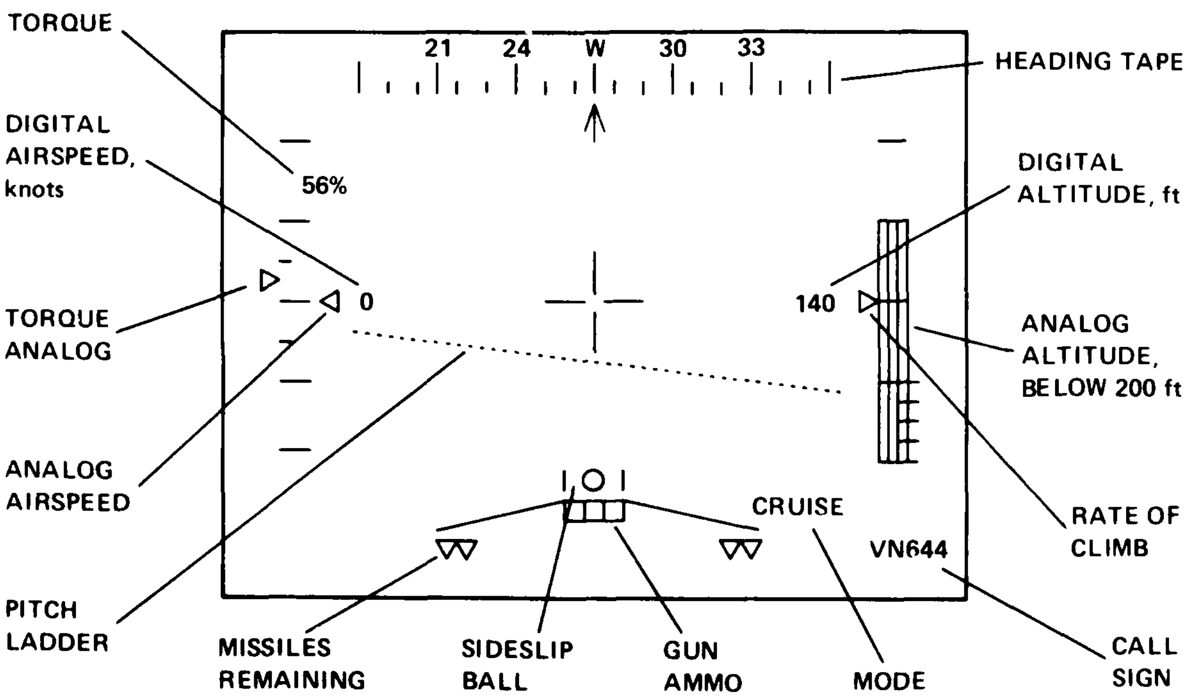


Figure 16. — Cruise head-up display.

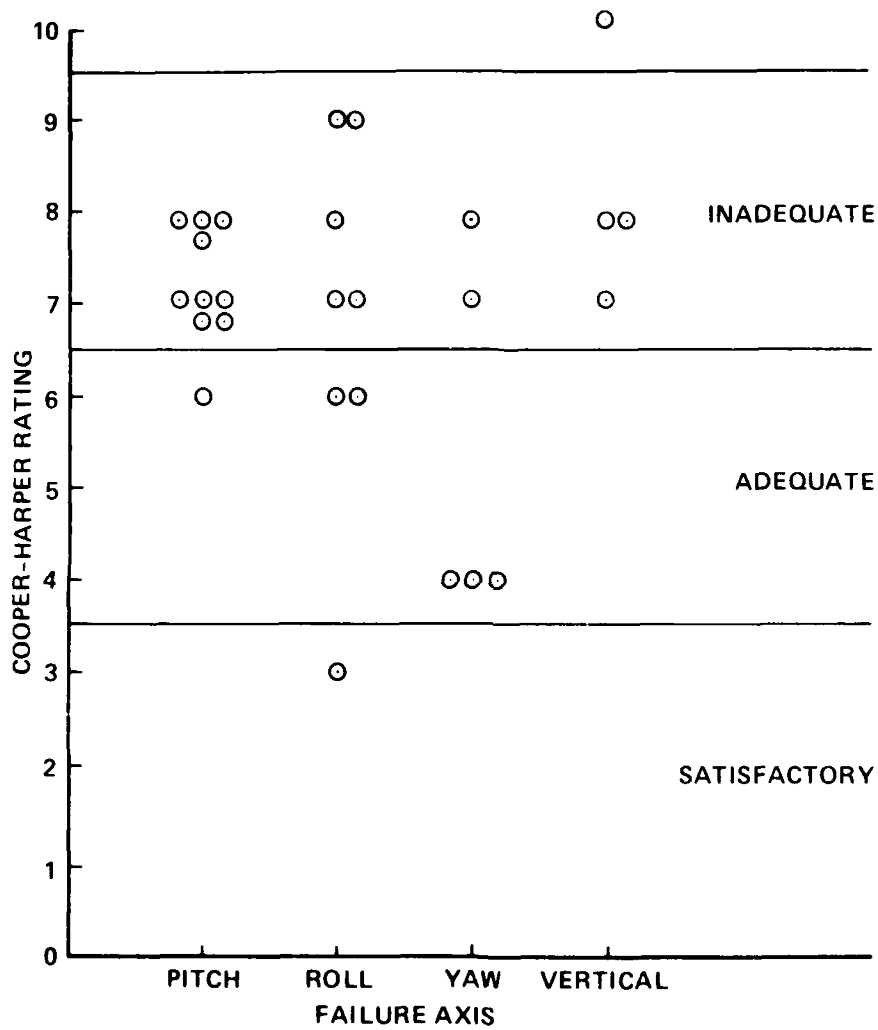


Figure 17. — Cooper-Harper ratings for the post-failed aircraft.

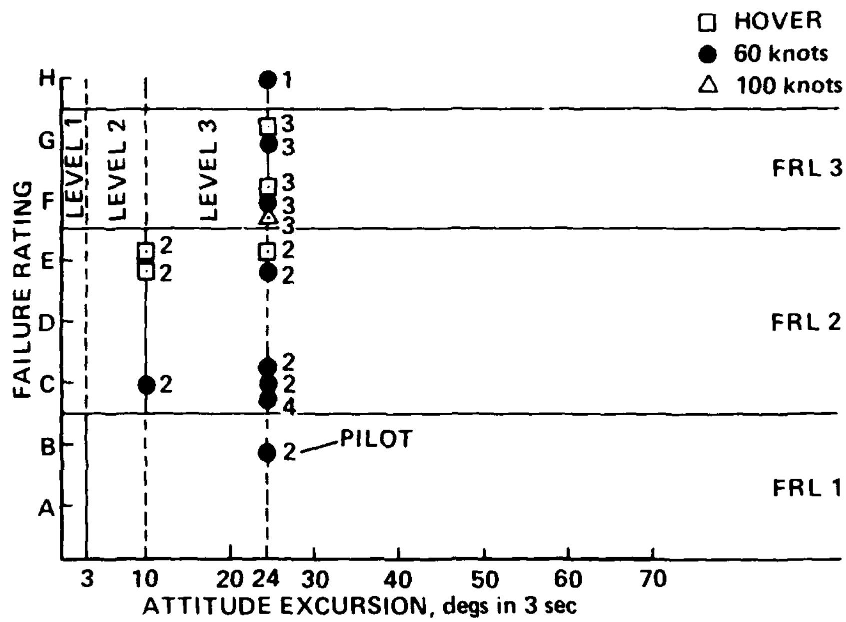


Figure 18. — Longitudinal axis failures.

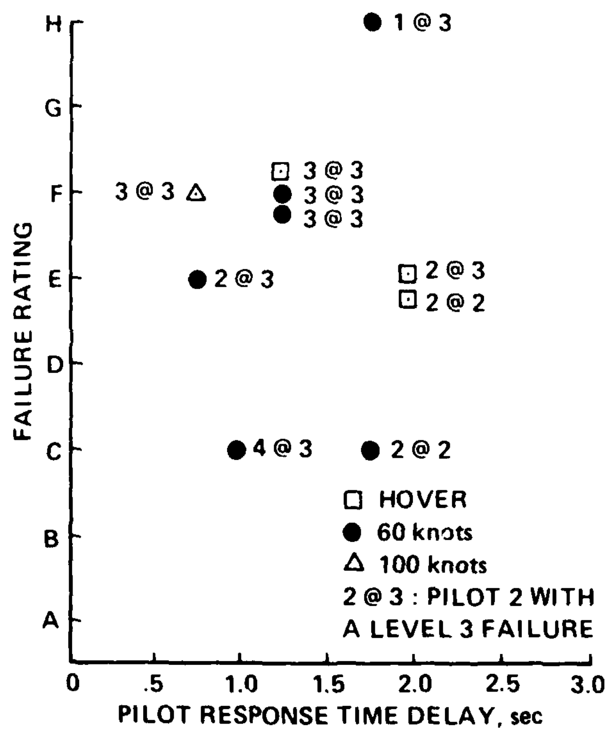


Figure 19. — Reaction time delays for longitudinal axis failures.

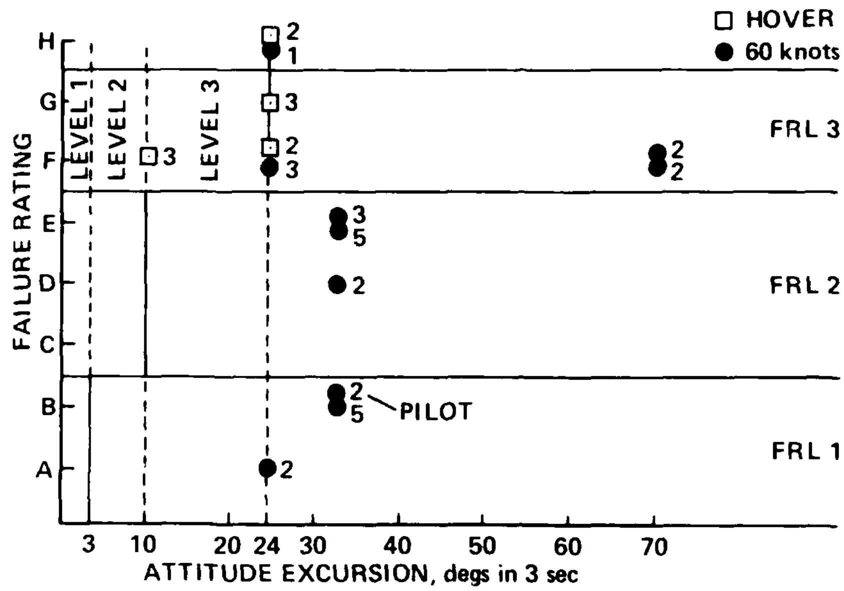


Figure 20. — Lateral axis failures.

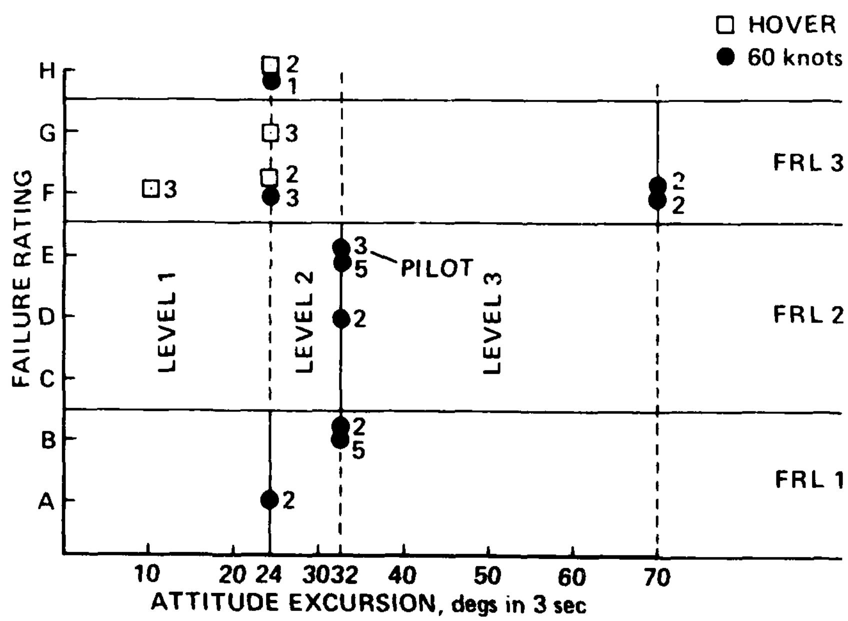


Figure 21. — Suggested revision for lateral axis failures.

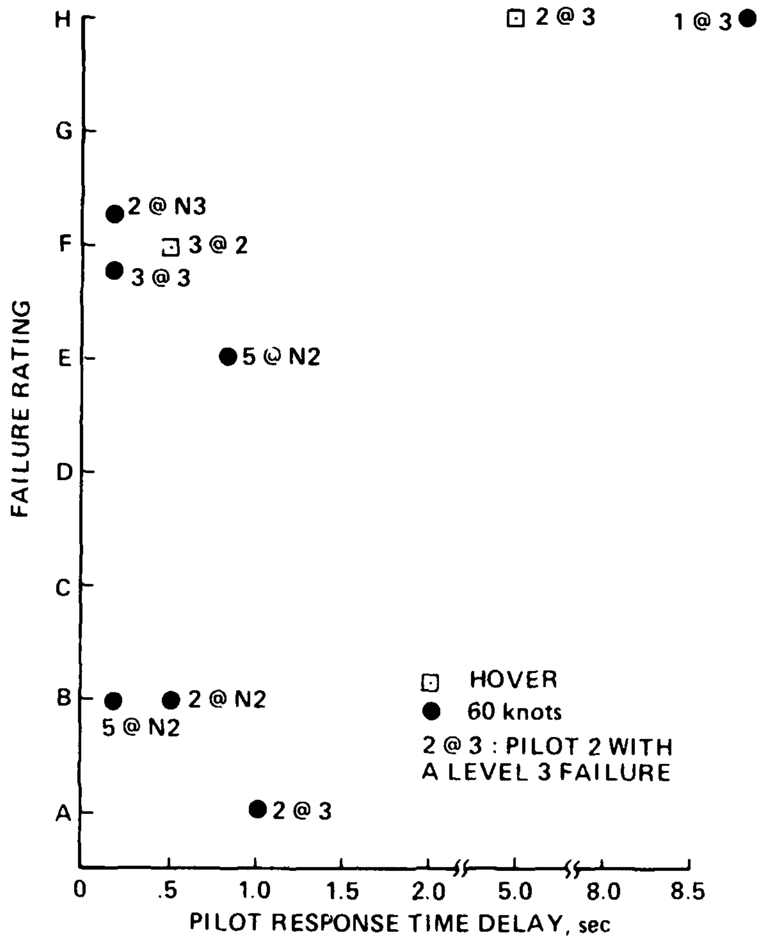


Figure 22. — Reaction time delays for lateral axis failures.

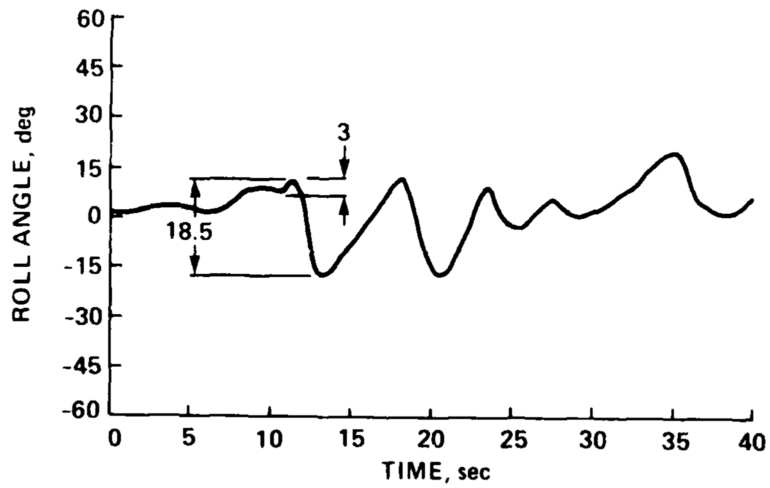


Figure 23. — Time history for new level 2 roll-axis failure.

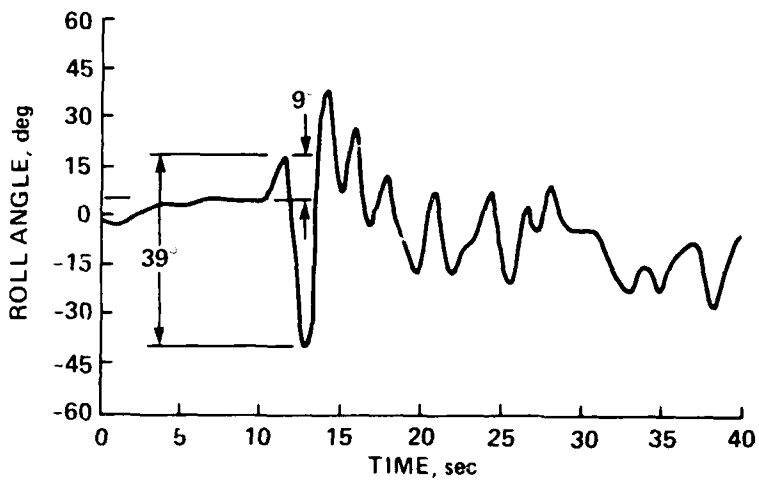


Figure 24. – Time history for new level 2 roll-axis failure.

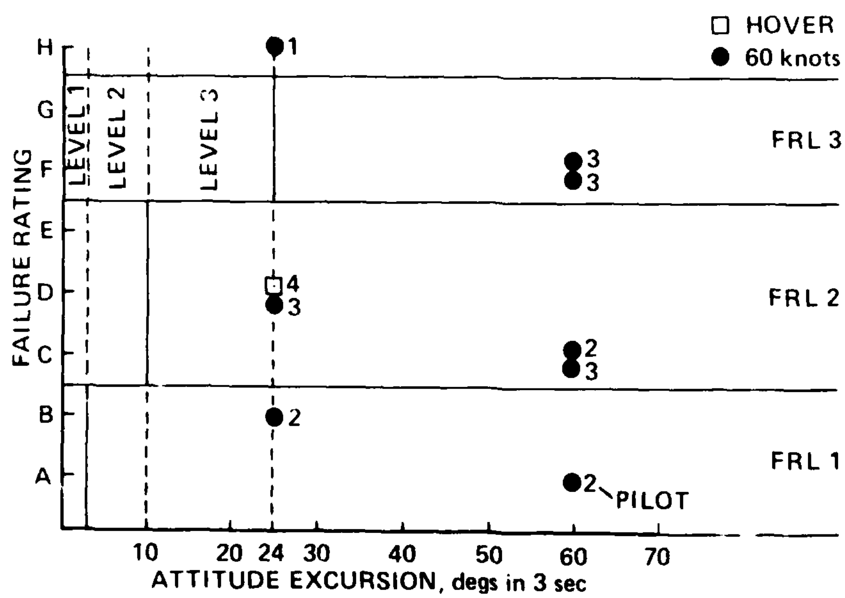


Figure 25. — Direction axis failures.

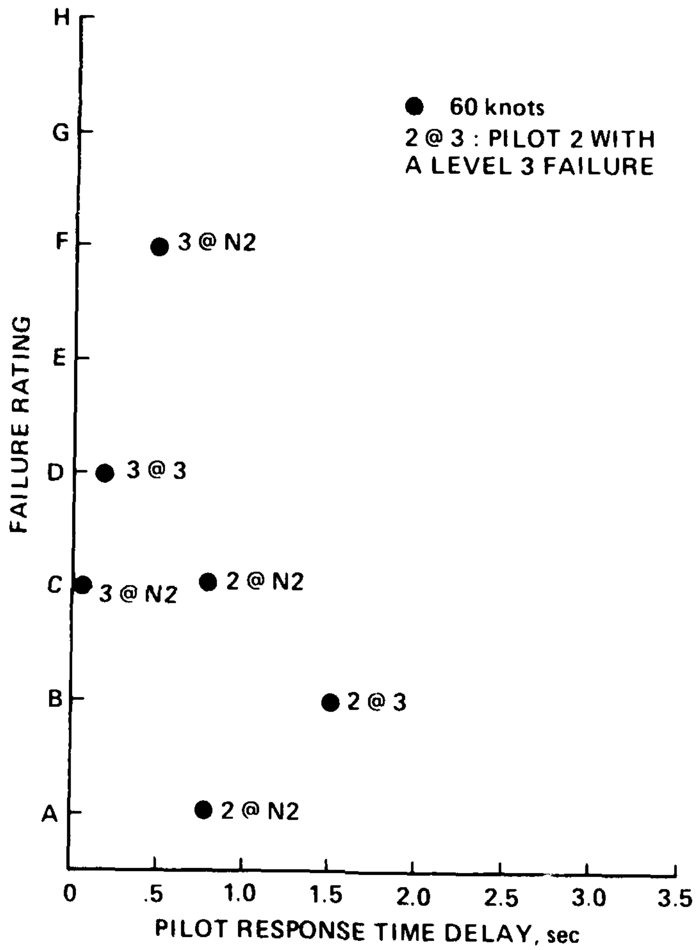


Figure 26. — Reaction time delays for directional axis failures.

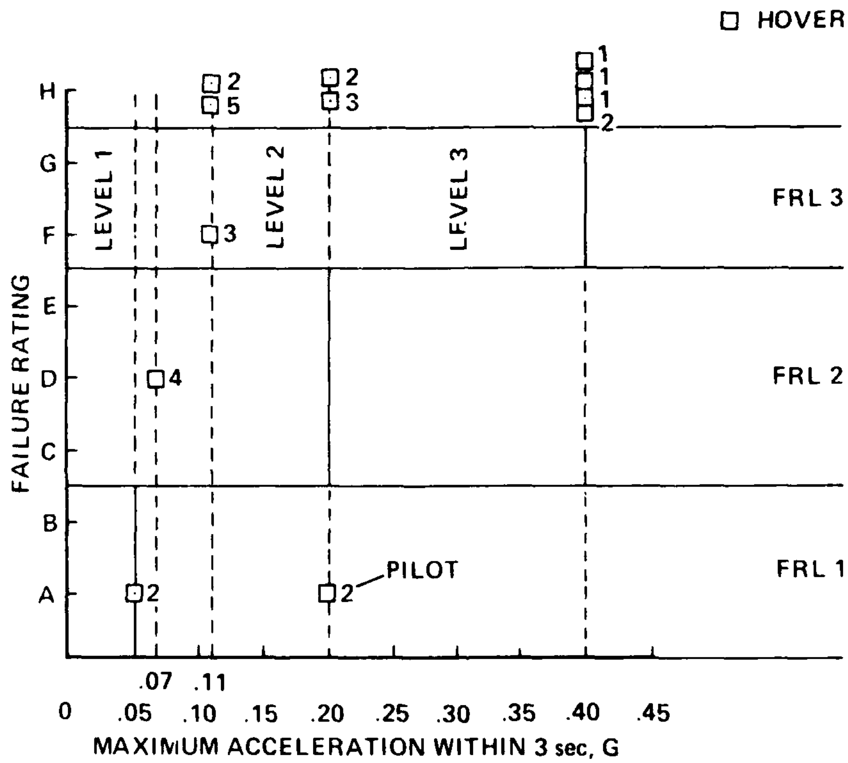


Figure 27. — Vertical axis failures.

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15. Supplementary Notes

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16. Abstract

A moving-base simulation was conducted to investigate a pilot's ability to recover from transients following single-axis hard-over failures of the flight-control system. The investigation was performed in conjunction with a host simulation that examined the influence of control modes on a single pilot's ability to perform various mission elements under high-workload conditions. The NASA Ames large-amplitude-motion Vertical Motion Simulator (VMS) was utilized, and the experimental variables were the failure axis, the severity of the failure, and the airspeed at which the failure occurred. Other factors, such as pilot workload and terrain and obstacle proximity at the time of failure, were kept as constant as possible within the framework of the host simulation task scenarios. No explicit failure warnings were presented to the pilot. Data from the experiment are shown, and pilot ratings are compared with the proposed handling-qualities requirements for military rotorcraft. Results indicate that the current proposed failure transient requirements may need revision.

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